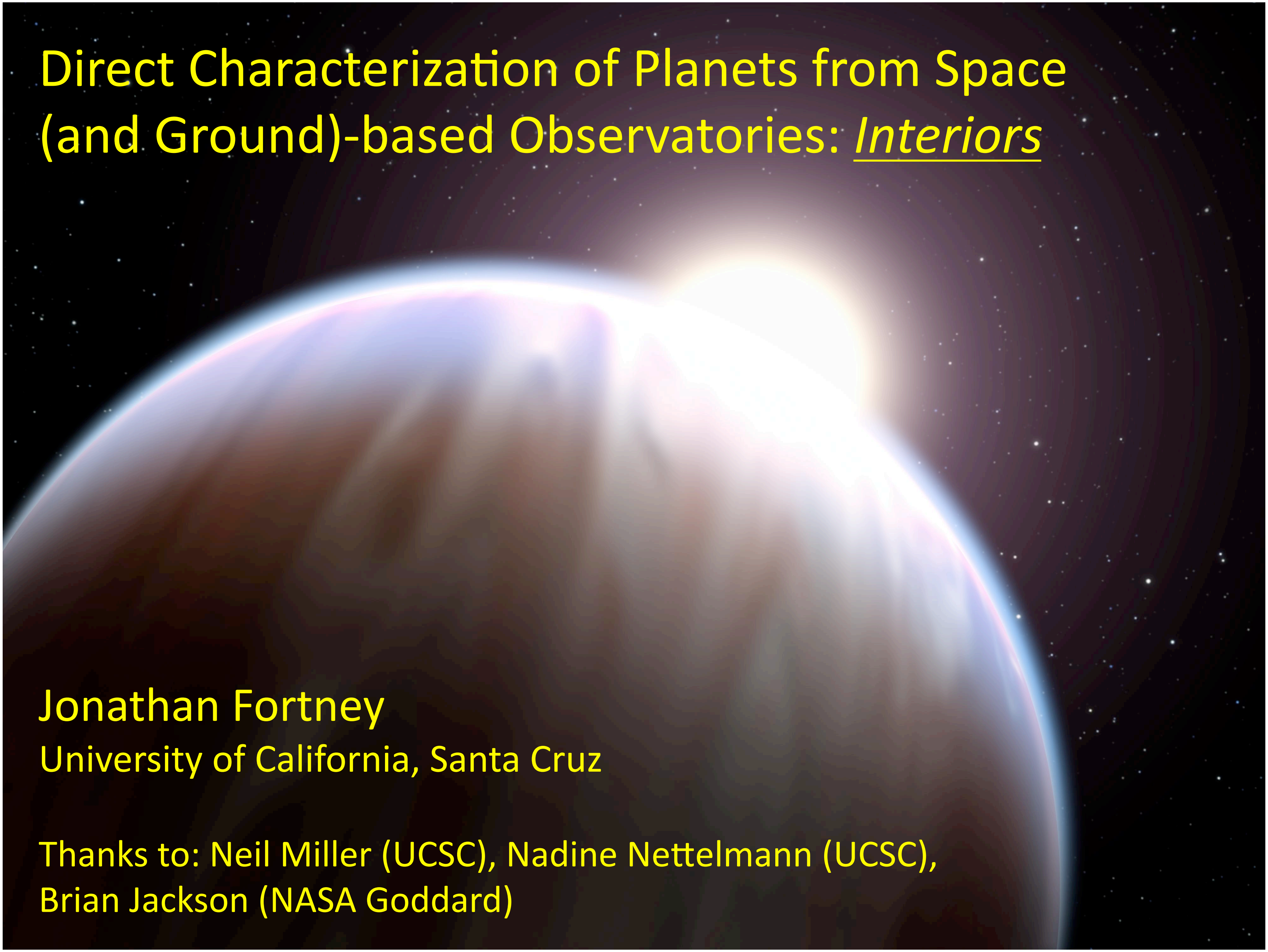
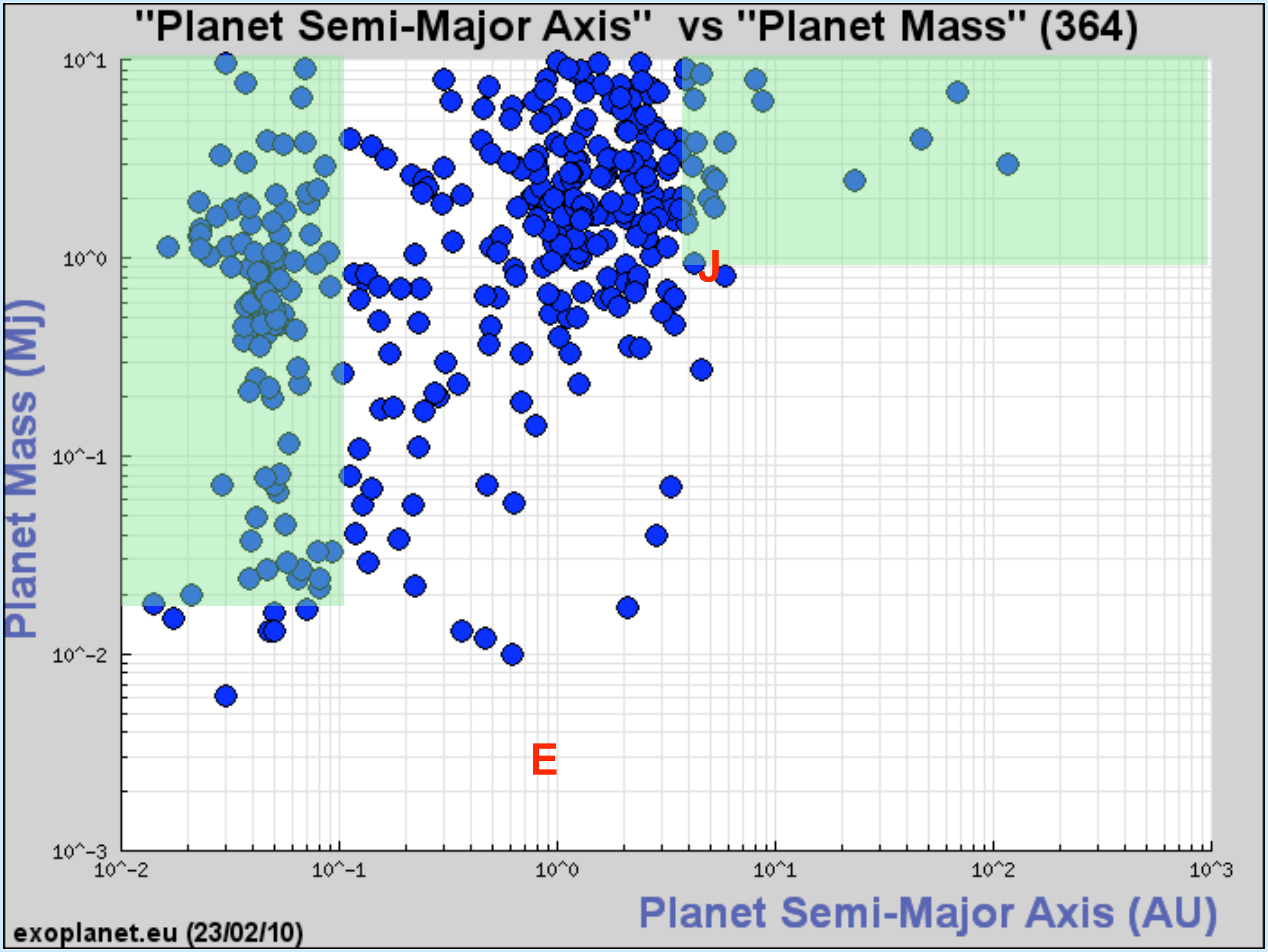


Direct Characterization of Planets from Space (and Ground)-based Observatories: *Interiors*

Jonathan Fortney
University of California, Santa Cruz

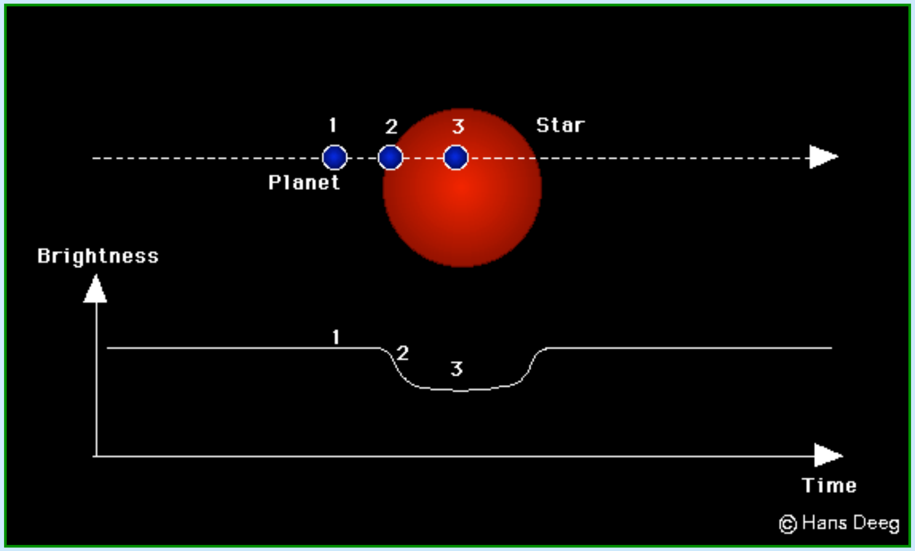
Thanks to: Neil Miller (UCSC), Nadine Nettelmann (UCSC), Brian Jackson (NASA Goddard)

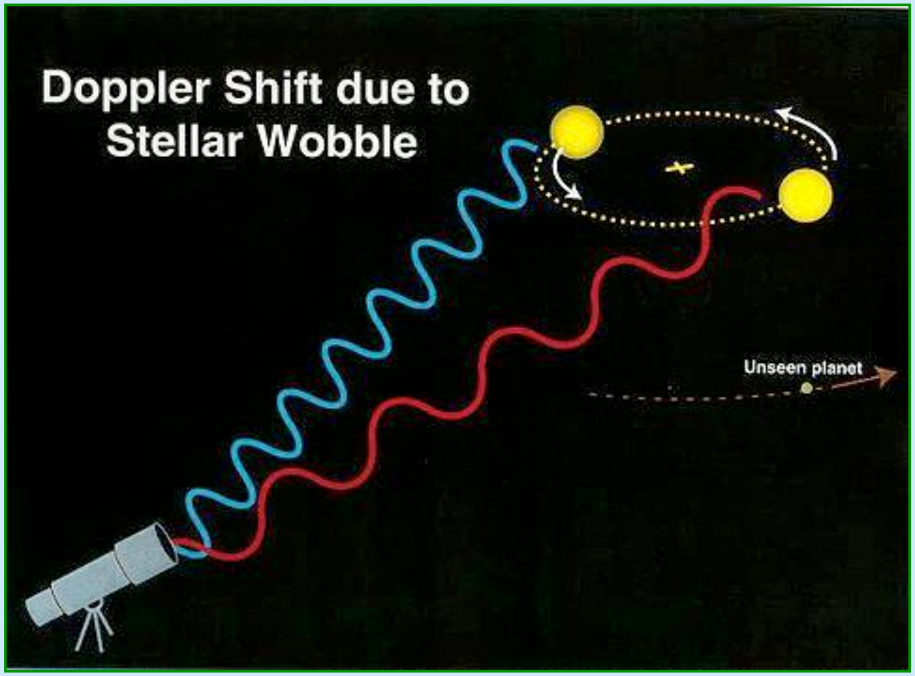
The Realm of Exoplanet Characterization: 2010/2011



Transiting Planets, Large and Small

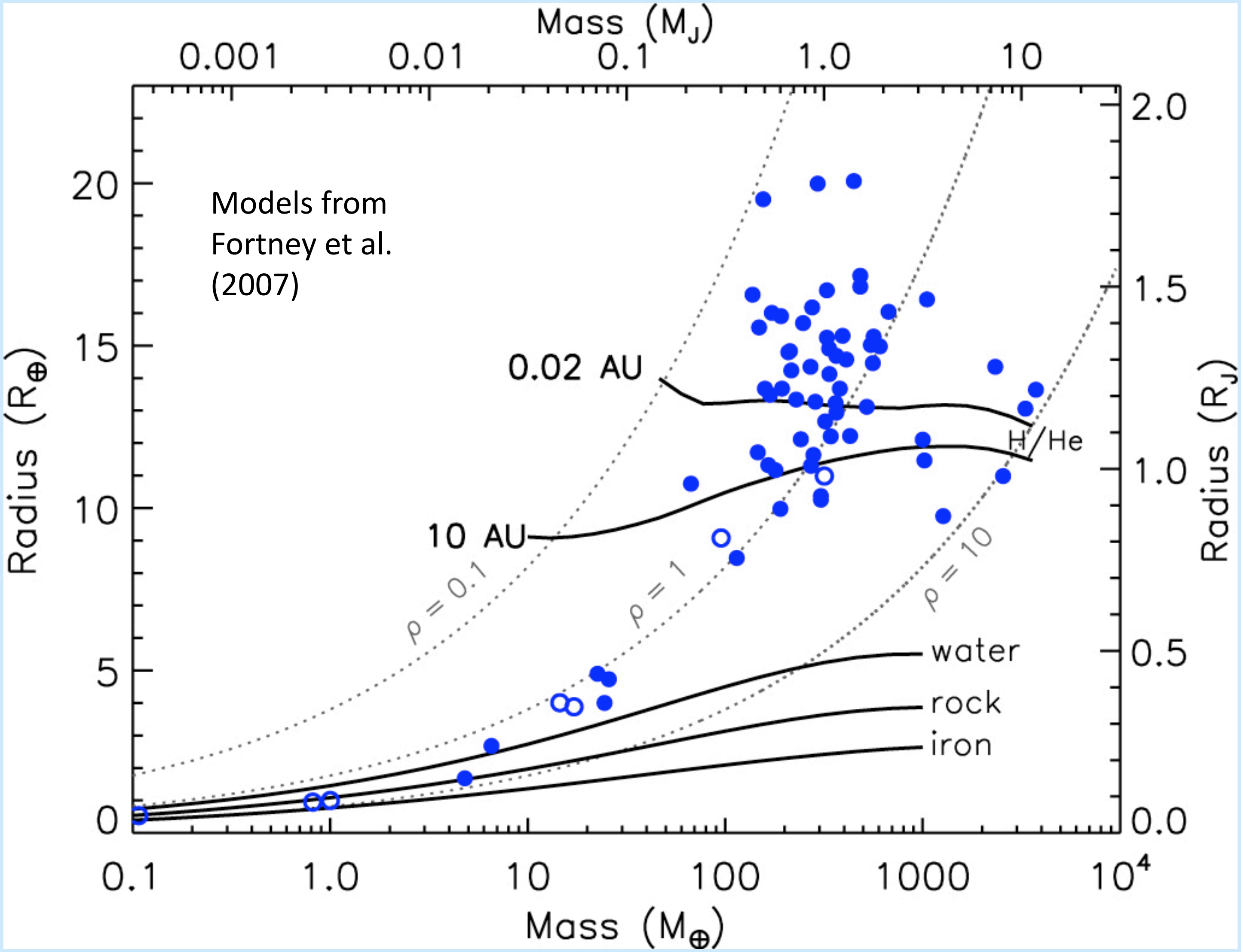
- 75 planets have now been seen to transit their parent stars
  - 70 “hot Jupiters”
  - 3 “hot Neptunes”
  - 2 “super Earths”
- Combination of planet radius and mass yield density --> composition
- Strong bias towards finding mass/large planets on short-period orbits





There is an incredibly diversity of worlds

- We can also **characterize** these planets, not just find them



Transiting Planets, Large and Small

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  - 3 "hot Neptunes"
  - 2 "super Earths"
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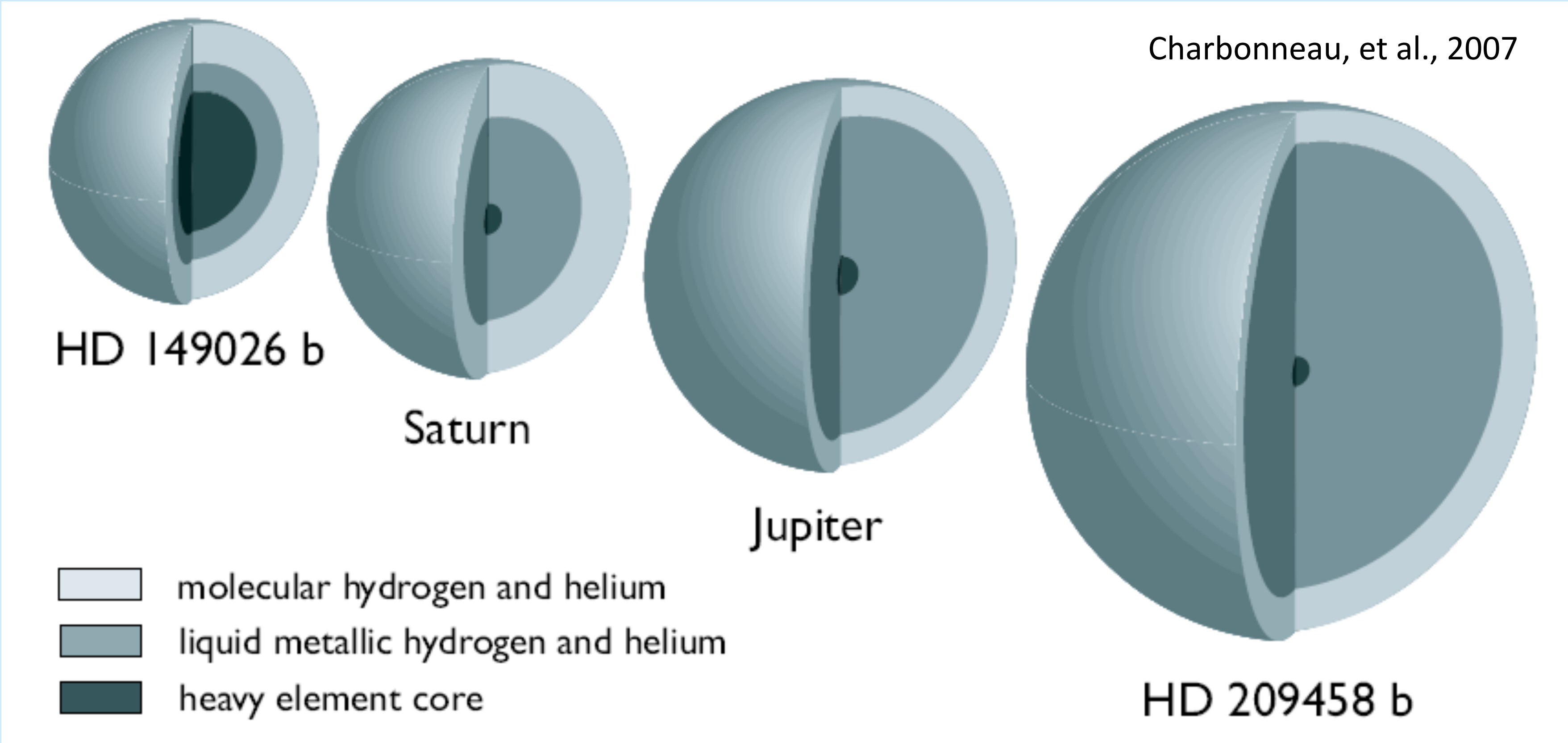
- Strong bias towards finding mass/large planets on short-period orbits

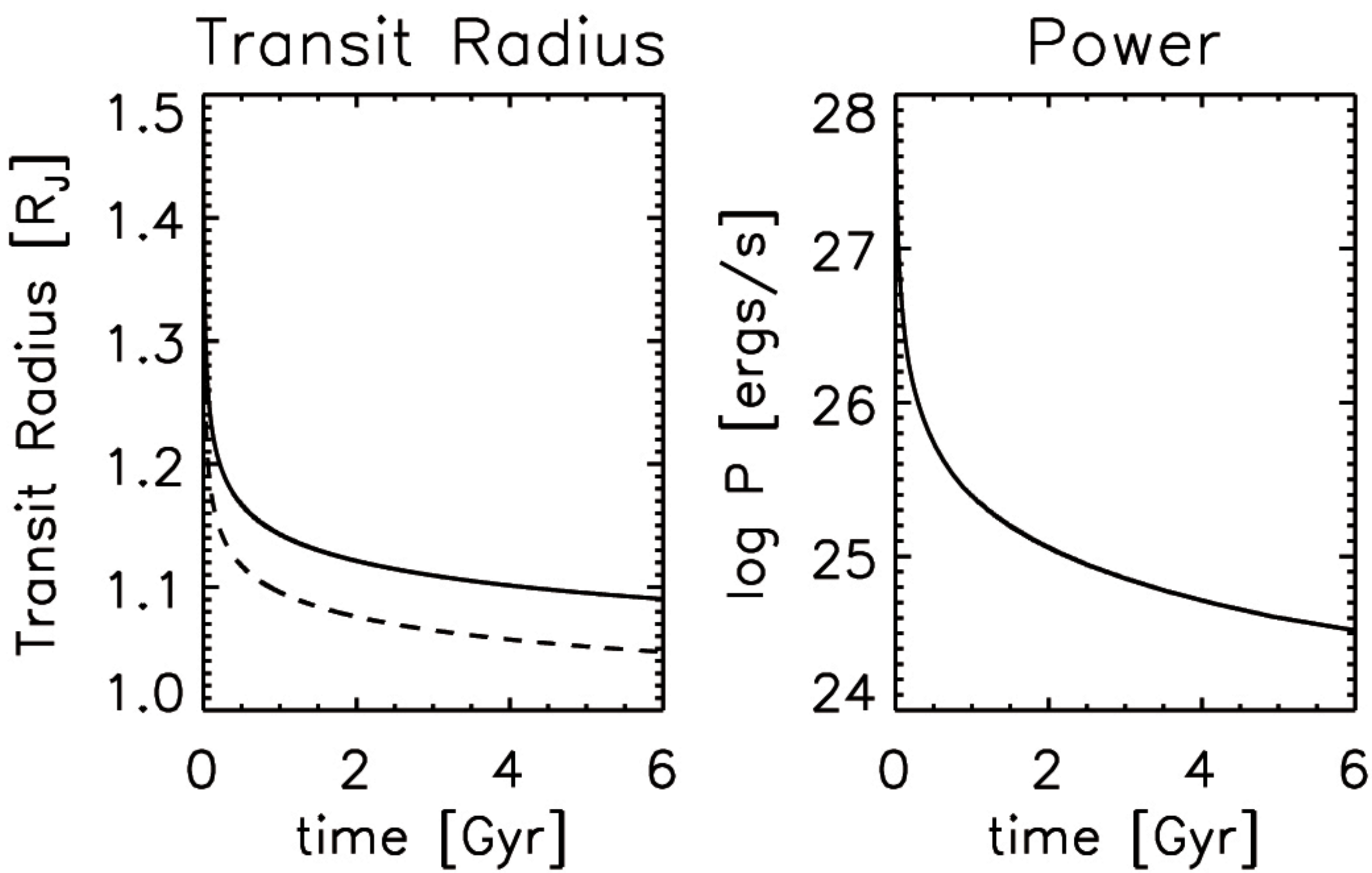
Study the group as a class of planets:
For instance, Tidal and Thermal Evolution of hot Jupiters

Study one particular object in detail:
Interior Structure of GJ 1214b



- There is considerable diversity amongst the known transiting planets
- Radii for planets of similar masses differ by a factor of two, which cannot happen for pure H/He objects

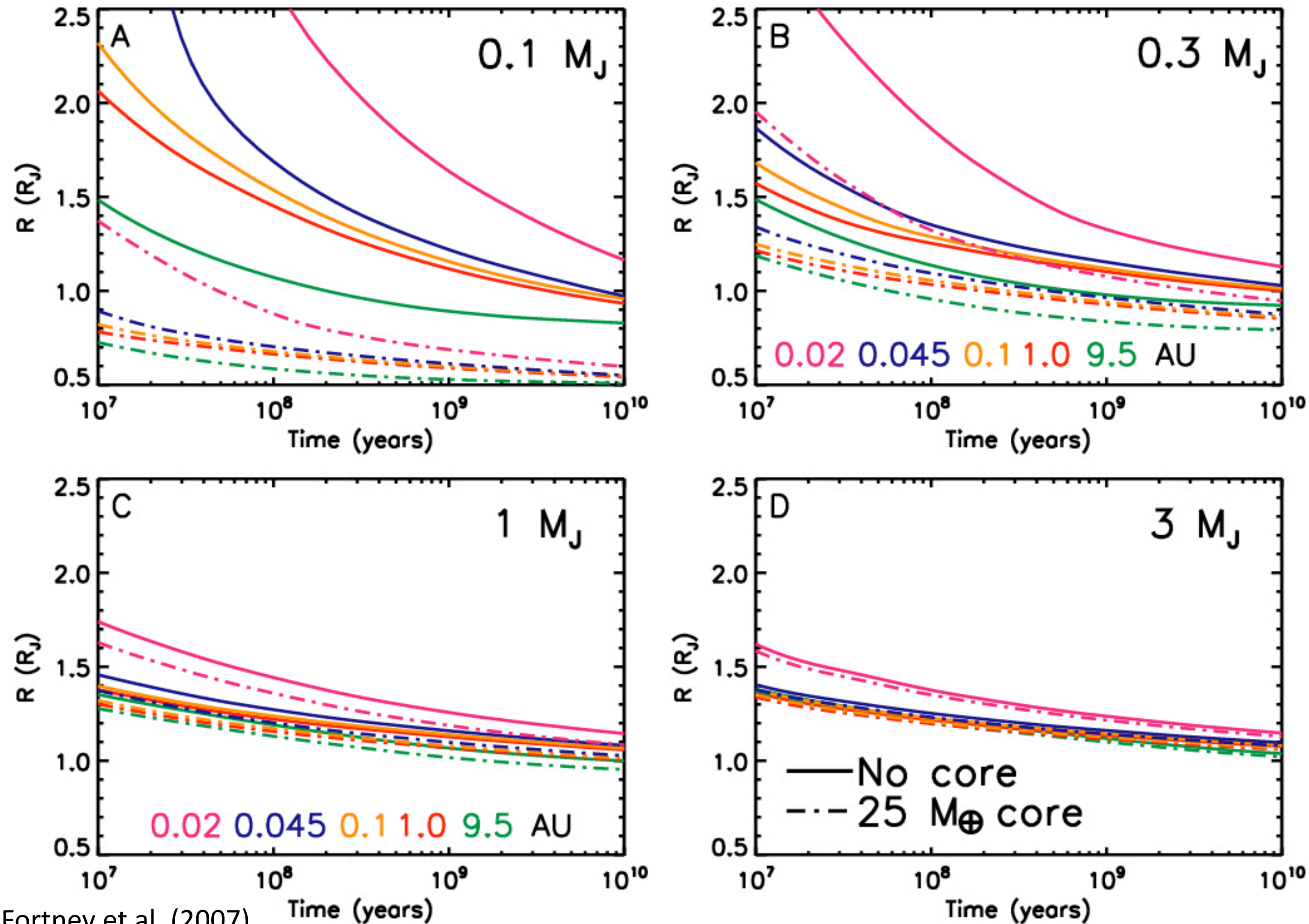
Building a Model, I: Standard Cooling and Contraction



Miller, Fortney, & Jackson (2009)

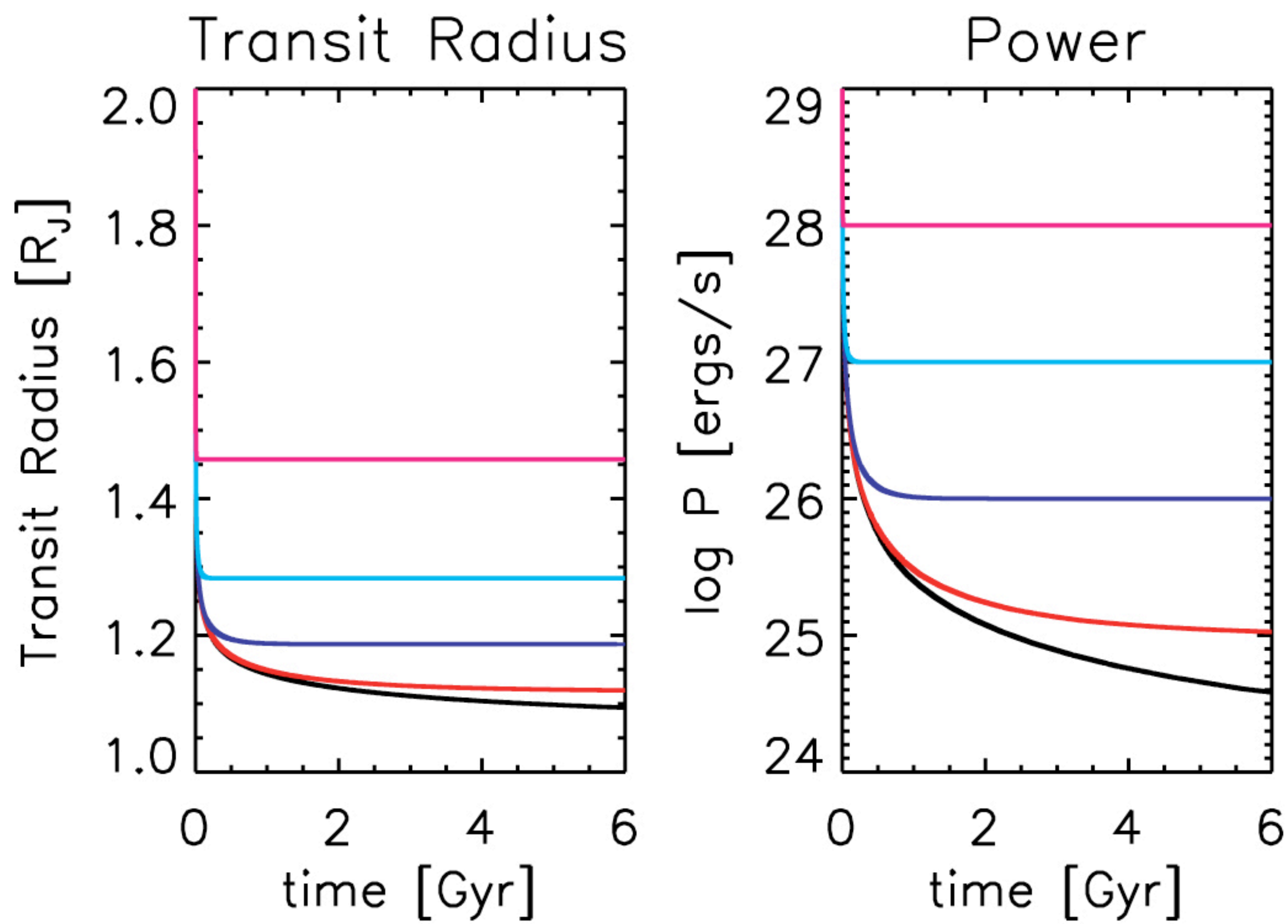
1 M_J planet with a 10 M_E core, at 0.05 AU from the Sun

At Gyr ages, ~1.3 R_J is the largest radius of a standard cooling model



Fortney et al. (2007)

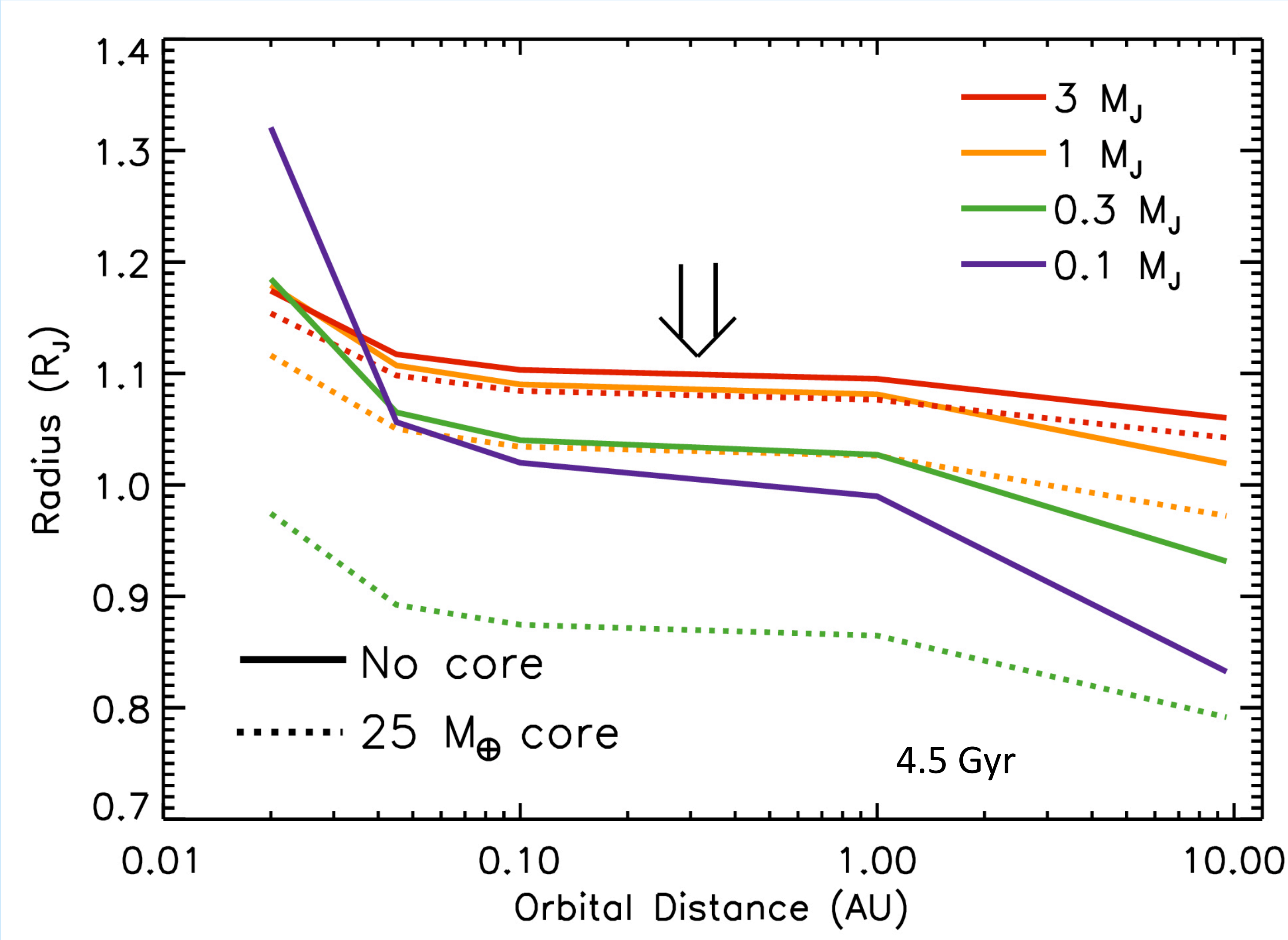
Building a Model, II: Additional Interior Power

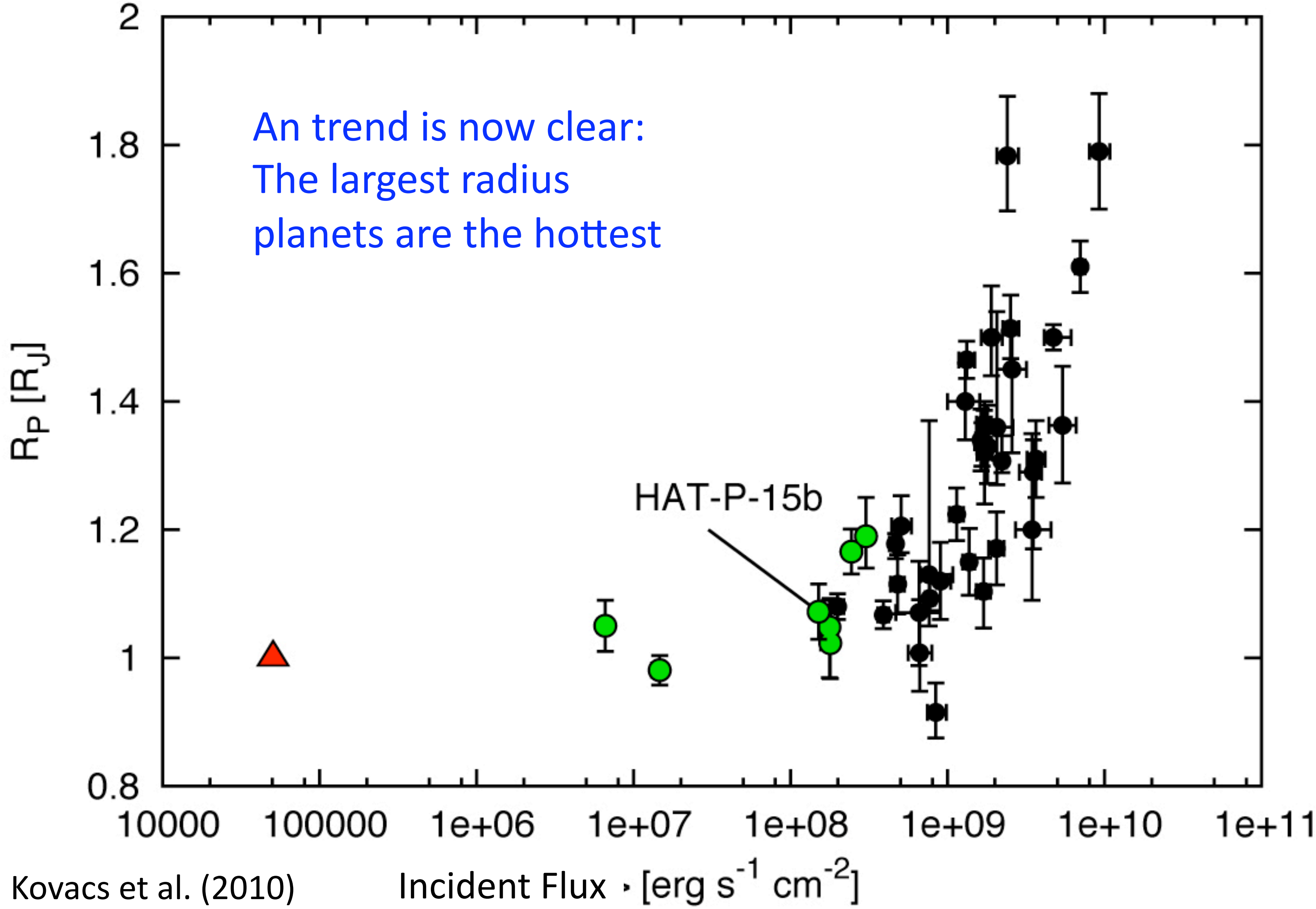


Miller, Fortney, & Jackson (2009)

1 M_J planet with a 10 M_E core, at 0.05 AU from the Sun

Planet Radius vs. Irradiation Level





Kovacs et al. (2010)

There is an incredibly diversity of worlds

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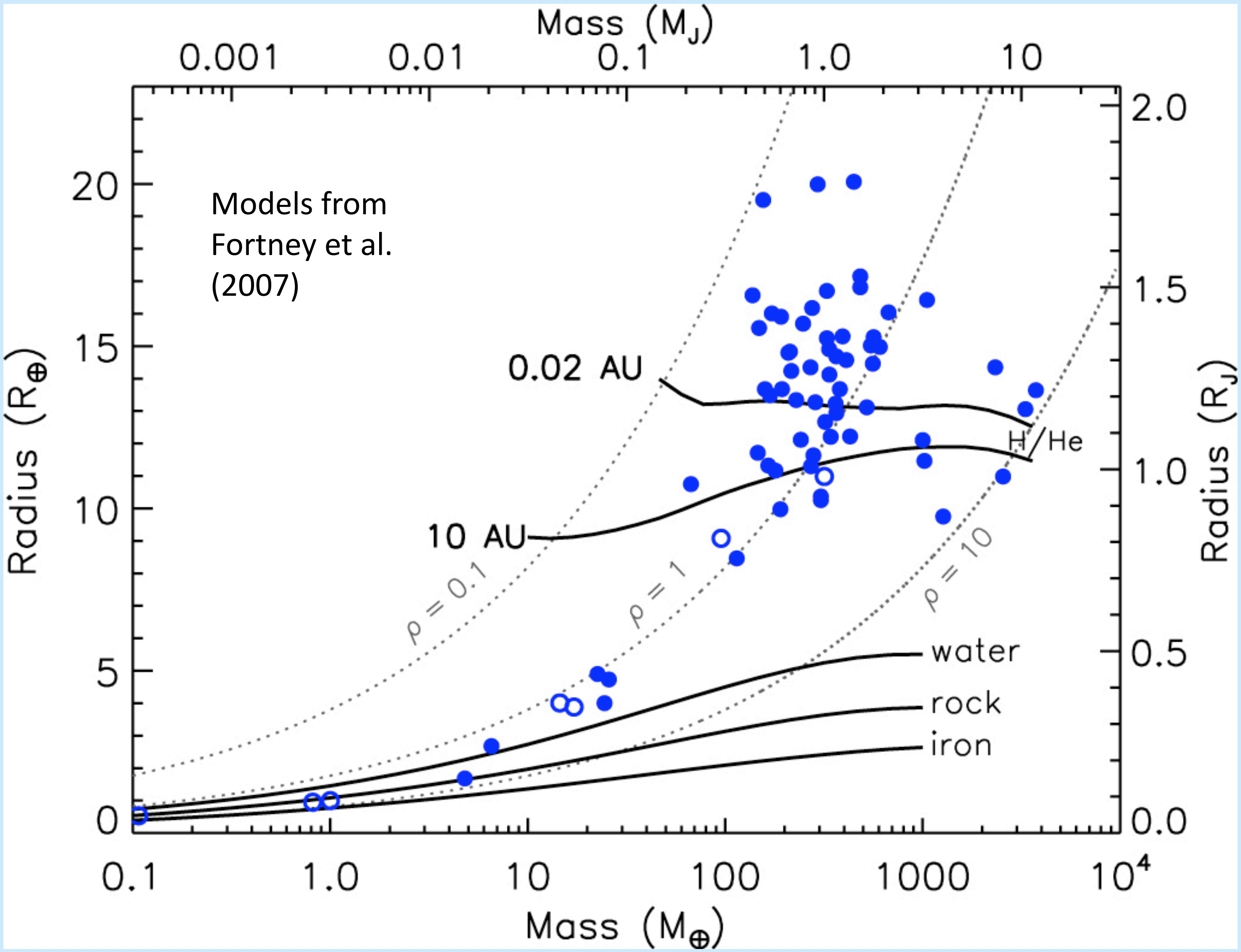


Explaining Large Radii

An area of active research!

Evolution of "51 Pegasus b-like" planets

T. Guillot[1] and A. P. Showman[2]

ON THE TIDAL INFLATION OF SHORT-PERIOD EXTRASOLAR PLANETS[1]

Peter Bodenheimer,[2] D. N. C. Lin,[2] and R. A. Mardling[2,3]

Received 2000 May 17; accepted 2000 October 11

OBLIQUITY TIDES ON HOT JUPITERS

Joshua N. Winn[1] and Matthew J. Holman

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

Received 2005 May 13; accepted 2005 June 20; published 2005 July 15

THERMAL TIDES IN FLUID EXTRASOLAR PLANETS

Phil Arras[1] and Aristotle Socrates[2]

[1] Department of Astronomy, University of Virginia, P.O. Box 400325, Charlottesville, VA 22904-4325, USA; arras@virginia.edu

[2] Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA; socrates@ias.edu

Received 2009 August 7; accepted 2010 February 16; published 2010 April 6

The effect of evaporation on the evolution of close-in giant planets

I. Baraffe[1], F. Selsis[2], G. Chabrier[1], T. S. Barman[3], F. Allard[1], P. H. Hauschildt[4], and H. Lammer[5]

CASSINI STATES WITH DISSIPATION: WHY OBLIQUITY TIDES CANNOT INFLATE HOT JUPITERS

Daniel C. Fabrycky, Eric T. Johnson, and Jeremy Goodman

Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544

Received 2007 March 16; accepted 2007 April 23

POSSIBLE SOLUTIONS TO THE RADIUS ANOMALIES OF TRANSITING GIANT PLANETS

A. Burrows,[1] I. Hubeny,[1] J. Budaj,[1,2] and W. B. Hubbard[3]

Received 2006 December 22; accepted 2007 February 9

HEAT TRANSPORT IN GIANT (EXO)PLANETS: A NEW PERSPECTIVE

Gilles Chabrier and Isabelle Baraffe[1,2]

Received 2007 March 6; accepted 2007 March 28; published

INFLATING AND DEFLATING HOT JUPITERS: COUPLED TIDAL AND THERMAL EVOLUTION OF KNOWN TRANSITING PLANETS

N. Miller[1], J. J. Fortney[1], and B. Jackson[2]

[1] Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA; neil@astro.ucsc.edu, jfortney@ucolick.org

[2] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA; bjackson@lpl.arizona.edu

Received 2009 May 4; accepted 2009 July 6; published 2009 August 21

TWO CLASSES OF HOT JUPITERS

Brad M. S. Hansen[1] and Travis Barman[2]

Received 2007 June 20; accepted 2007 August 23

TIDAL HEATING OF EXTRASOLAR PLANETS

Brian Jackson, Richard Greenberg, and Rory Barnes

Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721

Received 2007 December 5; accepted 2008 February 12

COUPLED EVOLUTION WITH TIDES OF THE RADIUS AND ORBIT OF TRANSITING GIANT PLANETS: GENERAL RESULTS

Laurent Ibgui and Adam Burrows

Department of Astrophysical Sciences, Peyton Hall, Princeton University, Princeton, NJ 08544, USA; ibgui@astro.princeton.edu, burrows@astro.princeton.edu

Received 2009 February 20; accepted 2009 June 4; published 2009 July 17

INFLATING HOT JUPITERS WITH OHMIC DISSIPATION

Konstantin Batygin and David J. Stevenson

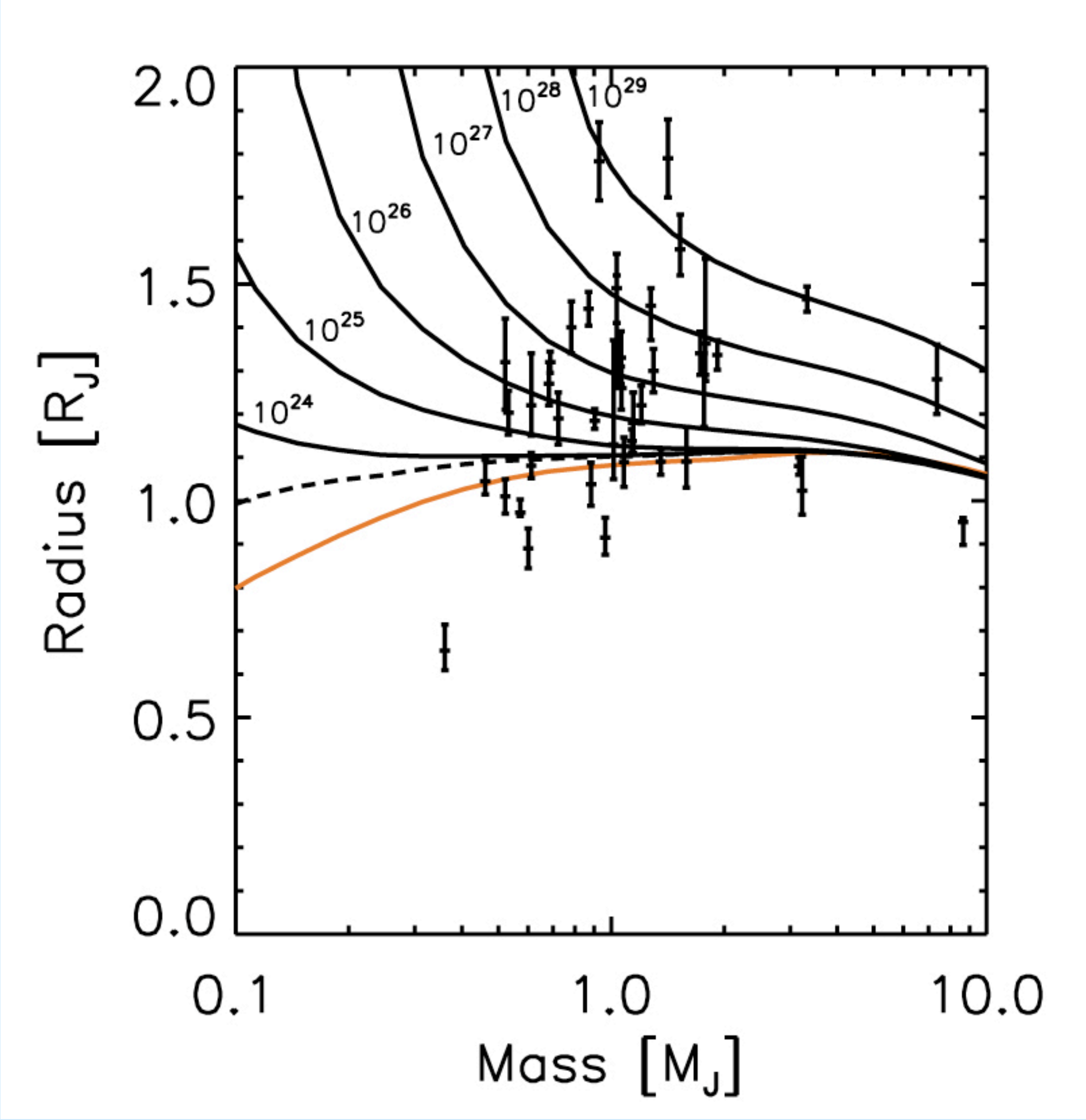
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA; kbatygin@gps.caltech.edu

Received 2010 February 18; accepted 2010 March 23; published 2010 April 15

Is tidal heating sufficient to explain bloated exoplanets? Consistent calculations accounting for finite initial eccentricity

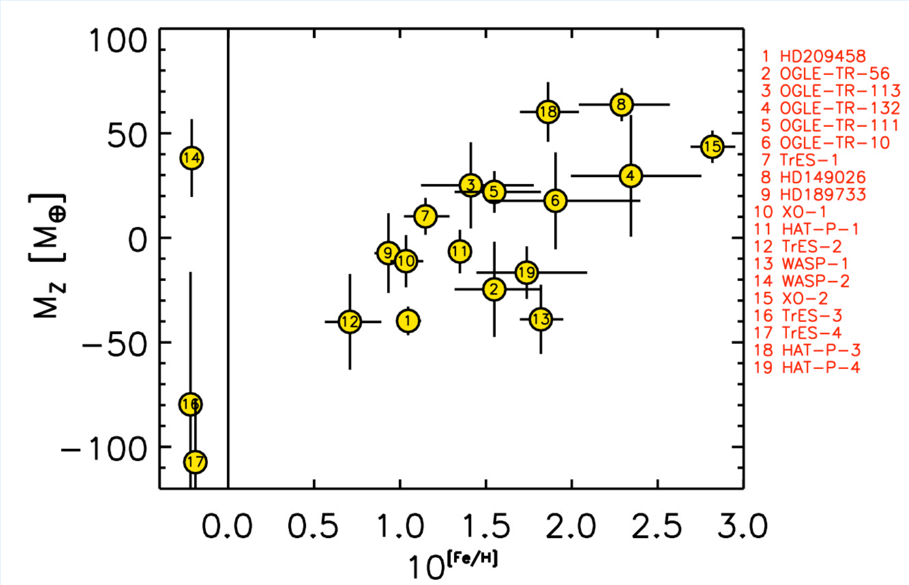
Jérémy Leconte[1], Gilles Chabrier[1], Isabelle Baraffe[1,2], and Benjamin Levrard[1]

Building a Model, II: Additional Interior Power

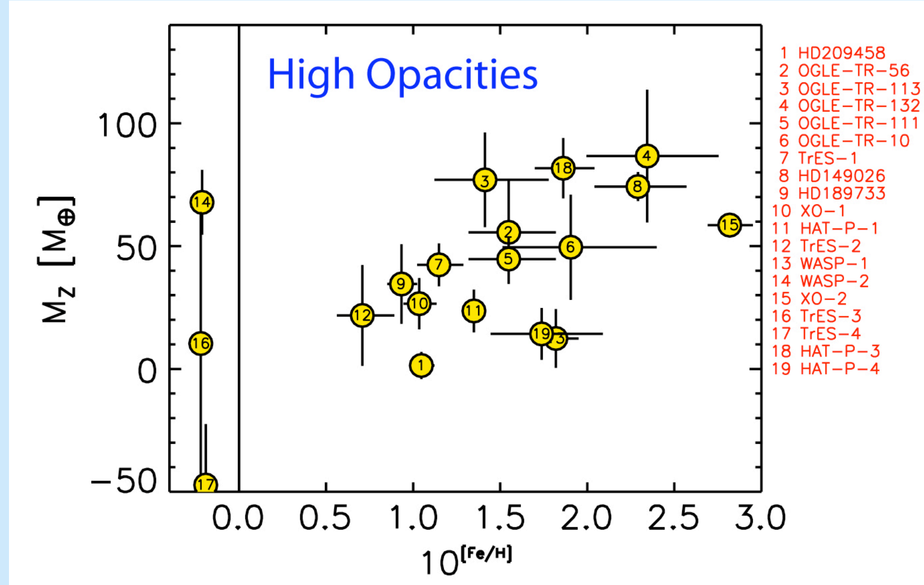


Miller, Fortney, & Jackson (2009)

- Lower mass planets more easily influenced by a given magnitude of power source
- Power levels are generally small compared to Irradiation from the parent star ~10^{29} erg/s
- Transit radius effect only important at low gravity



100
50
0
−50
−100
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$10^{[Fe/H]}$
M_Z [$M_\oplus$]
1 HD209458
2 OGLE−TR−56
3 OGLE−TR−113
4 OGLE−TR−132
5 OGLE−TR−111
6 OGLE−TR−10
7 TrES−1
8 HD149026
9 HD189733
10 XO−1
11 HAT−P−1
12 TrES−2
13 WASP−1
14 WASP−2
15 XO−2
16 TrES−3
17 TrES−4
18 HAT−P−3
19 HAT−P−4



High Opacities
100
50
0
−50
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$10^{[Fe/H]}$
M_Z [$M_\oplus$]
1 HD209458
2 OGLE−TR−56
3 OGLE−TR−113
4 OGLE−TR−132
5 OGLE−TR−111
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16 TrES−3
17 TrES−4
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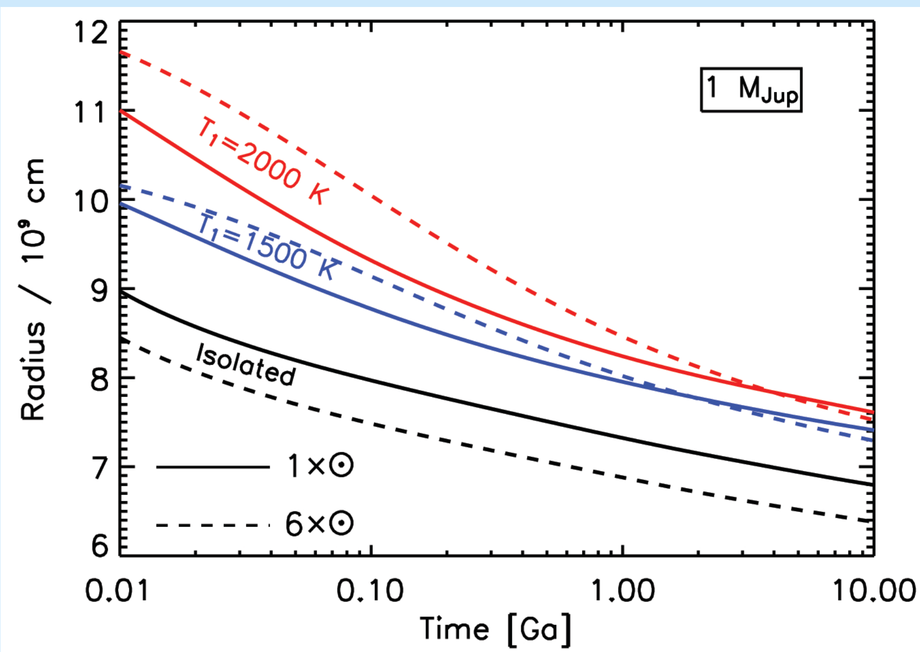
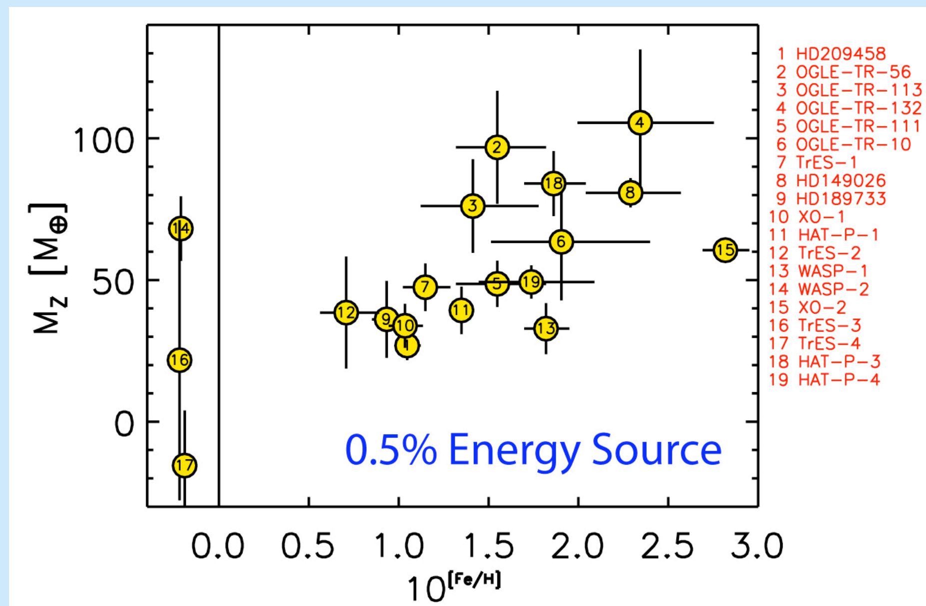
19 HAT−P−4



1 M_{Jup}
T_1=2000 K
T_1=1500 K
Isolated
1×☉
6×☉
12
11
10
9
8
7
6
0.01
0.10
1.00
10.00
Time [Ga]
Radius / 10^9 cm



0.5% Energy Source
100
50
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$10^{[Fe/H]}$
M_Z [$M_\oplus$]
1 HD209458
2 OGLE−TR−56
3 OGLE−TR−113
4 OGLE−TR−132
5 OGLE−TR−111
6 OGLE−TR−10
7 TrES−1
8 HD149026
9 HD189733
10 XO−1
11 HAT−P−1
12 TrES−2
13 WASP−1
14 WASP−2
15 XO−2
16 TrES−3
17 TrES−4
18 HAT−P−3
19 HAT−P−4

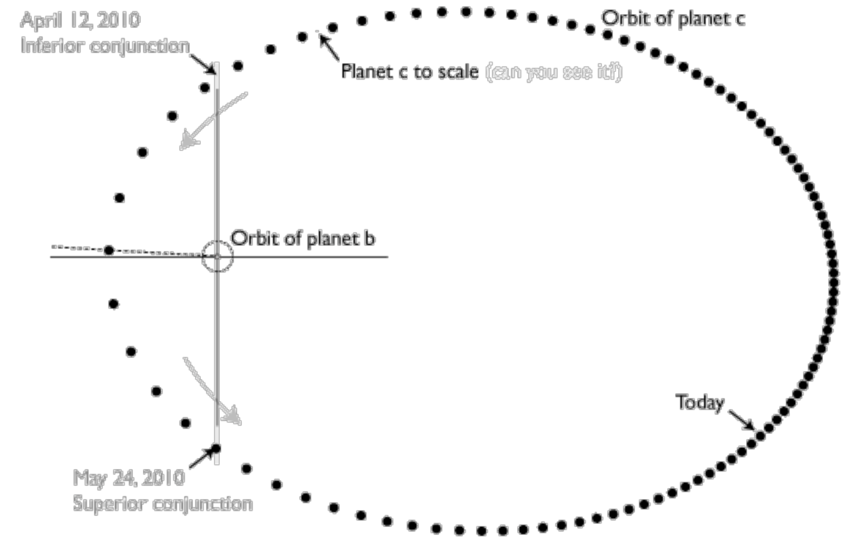
Transits in multi-planets systems: A path towards direct interior constraints: k_{2b}

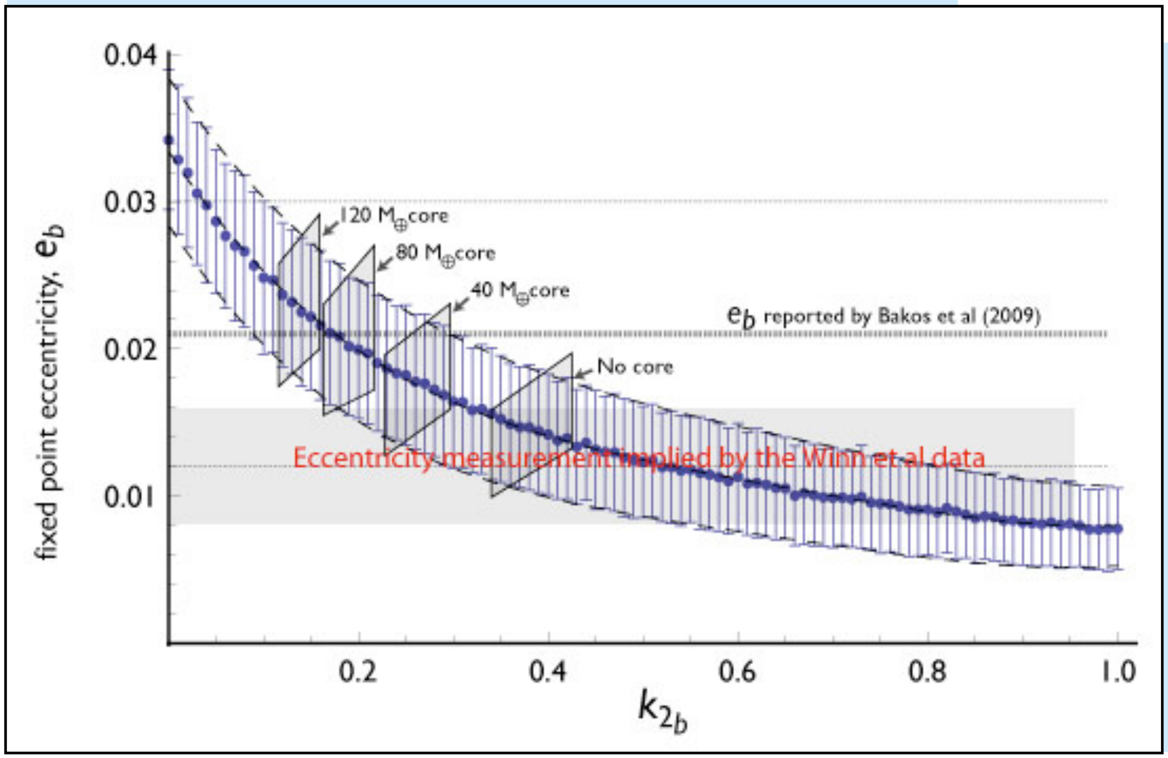
calculation of k_{2b} is straightforward (Sterne 1939),[3]

$$k_{2b} = \frac{3 - \eta_2(R_{Pl})}{2 + \eta_2(R_{Pl})}\,, \qquad (13)$$

where $\eta_2(R_{Pl})$ is obtained by integrating an ordinary differential equation for $\eta_2(r)$ radially outward from $\eta_2(0) = 0$,

$$r\frac{d\eta_2}{dr} + \eta_2^2 - \eta_2 - 6 + \frac{6\rho}{\rho_m}(\eta_2 + 1) = 0\,, \qquad (14)$$

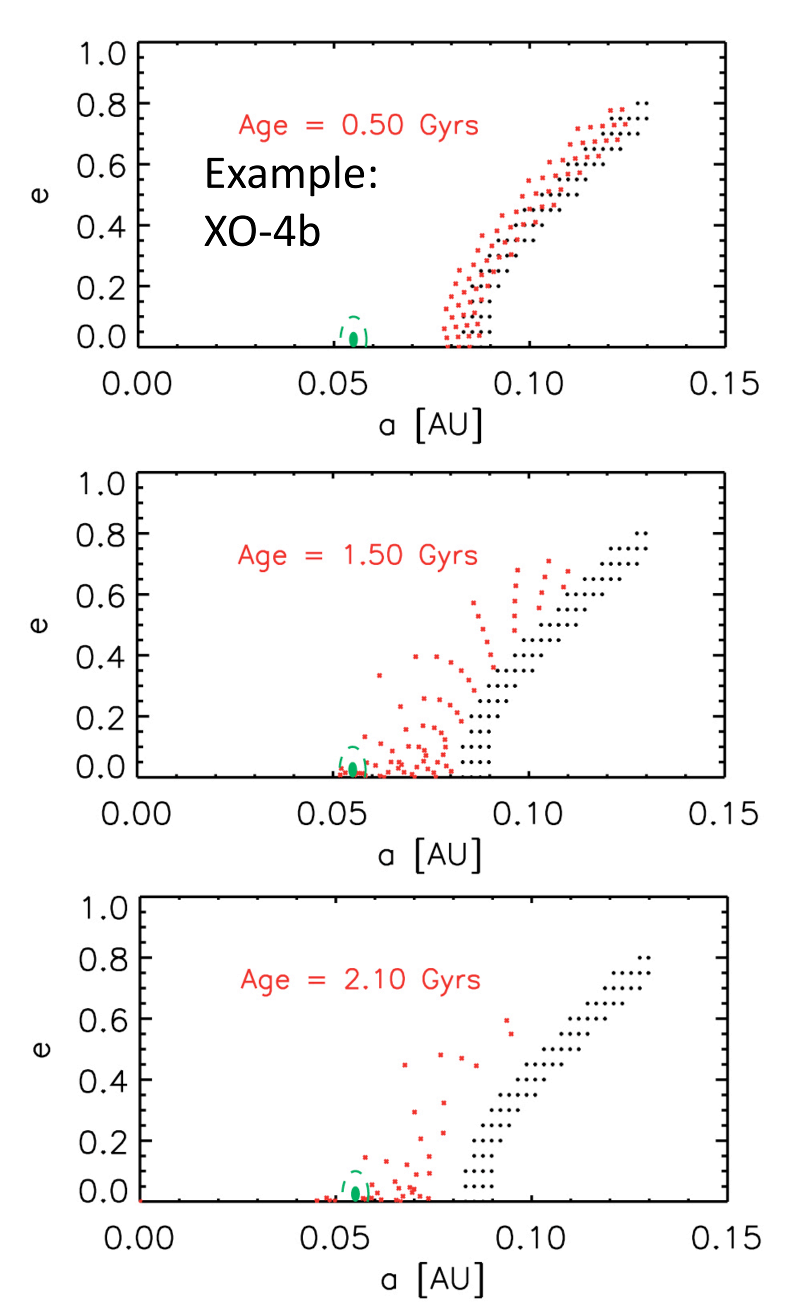




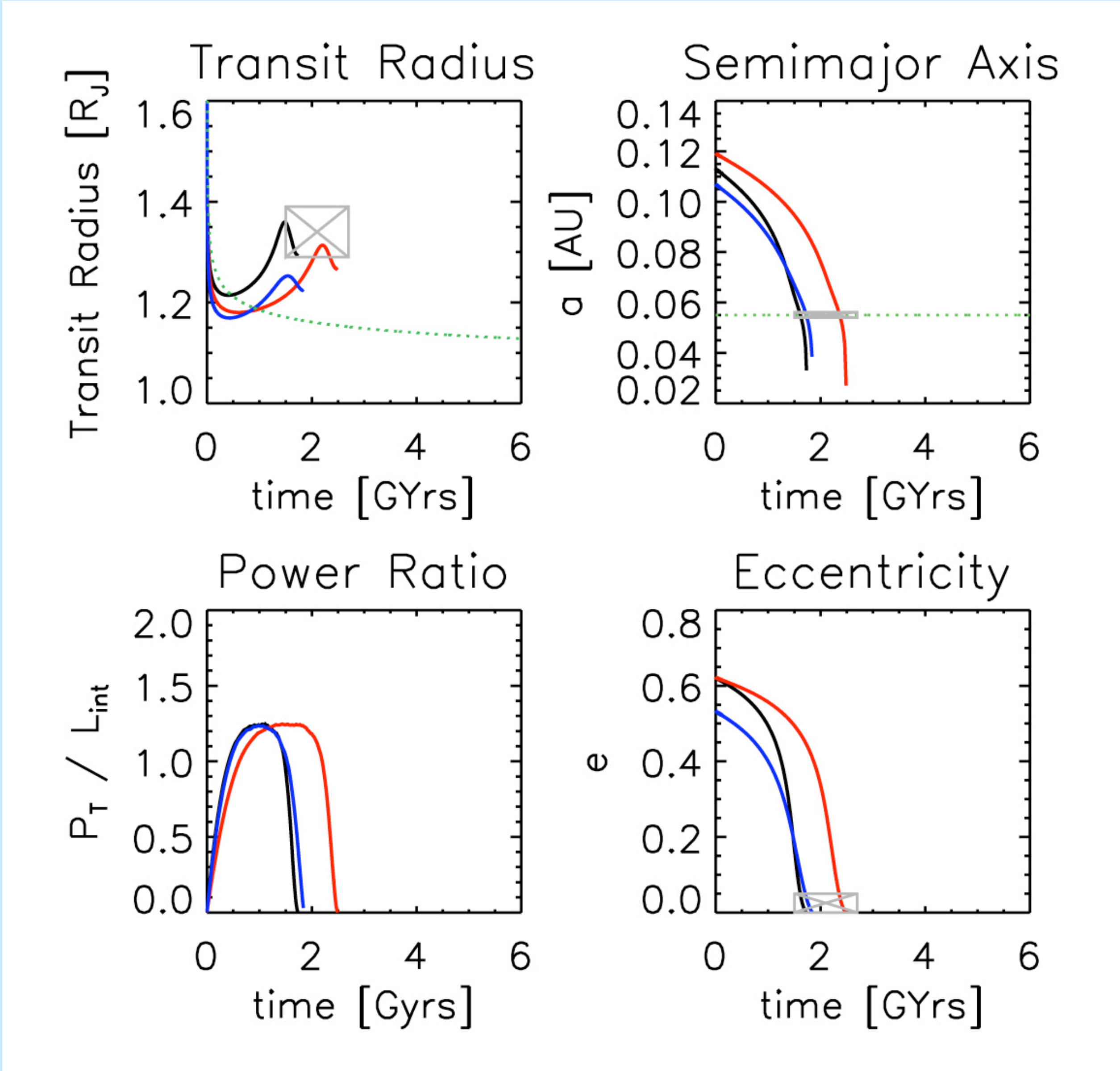
Wu & Goldreich (2005)
Batygin et al. (2009)

Miller, Fortney, and Jackson (2009): Tidal heating can probably inflate some planets, but it is not a cure-all

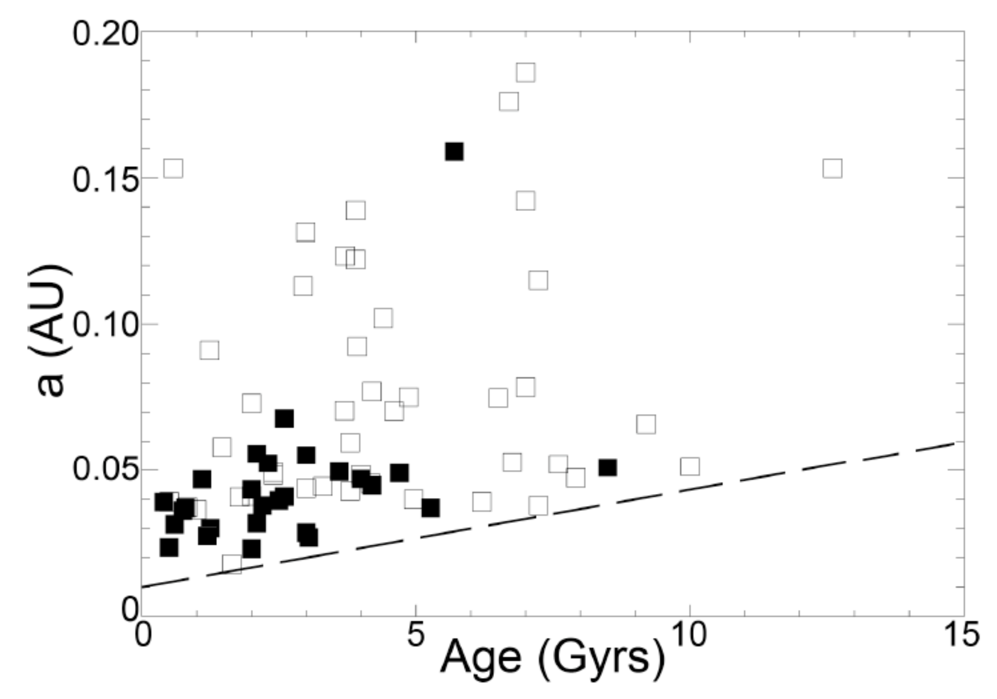
1. $Q_p=10^5$ and $10^{6.5}$, $Q_s=10^5$, with additional runs at $Q_s=10^6,10^7$
2. Measured *a*, *e*, age, with error bars
3. Large initial grid of *a* and *e* for each system
4. Evolve forward in time to search for pathways that match the current *a*, *e*, age.
5. What is the radius for models that make that match?

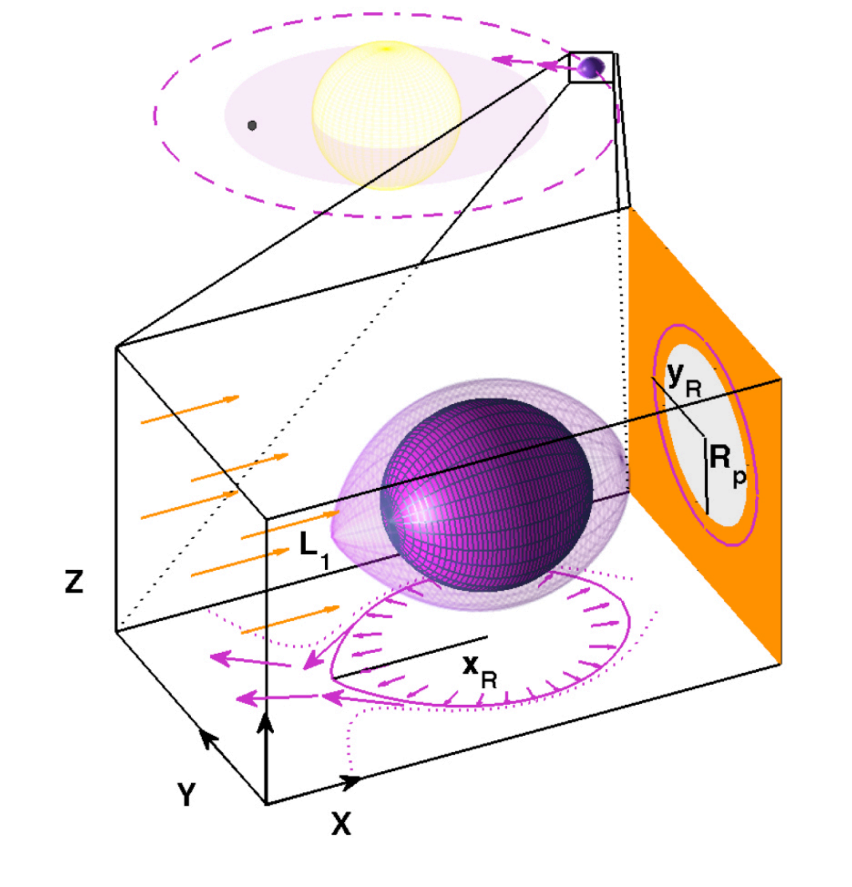


Example XO-4b: Inflated, Current e ≈ 0, but not well constrained



Jackson et al. (2009) *ApJ*
"Observational Evidence for Tidal Disruption of Exoplanets"



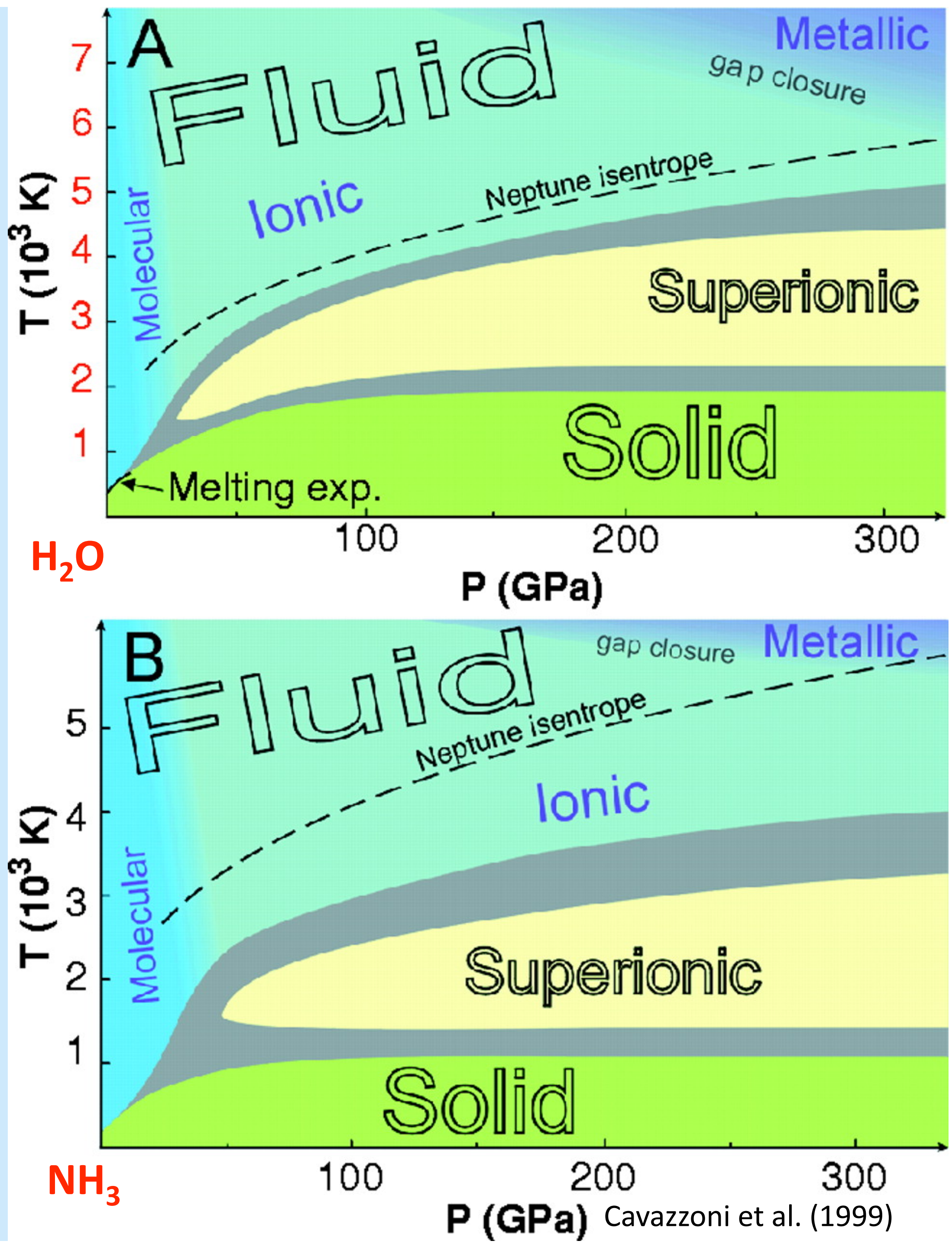


Li, Miller, Lin, & Fortney (2010) *Nature*
Ongoing loss of planet Wasp-12b

Fossati et al. (2010), ApJ: disk around Wasp-12

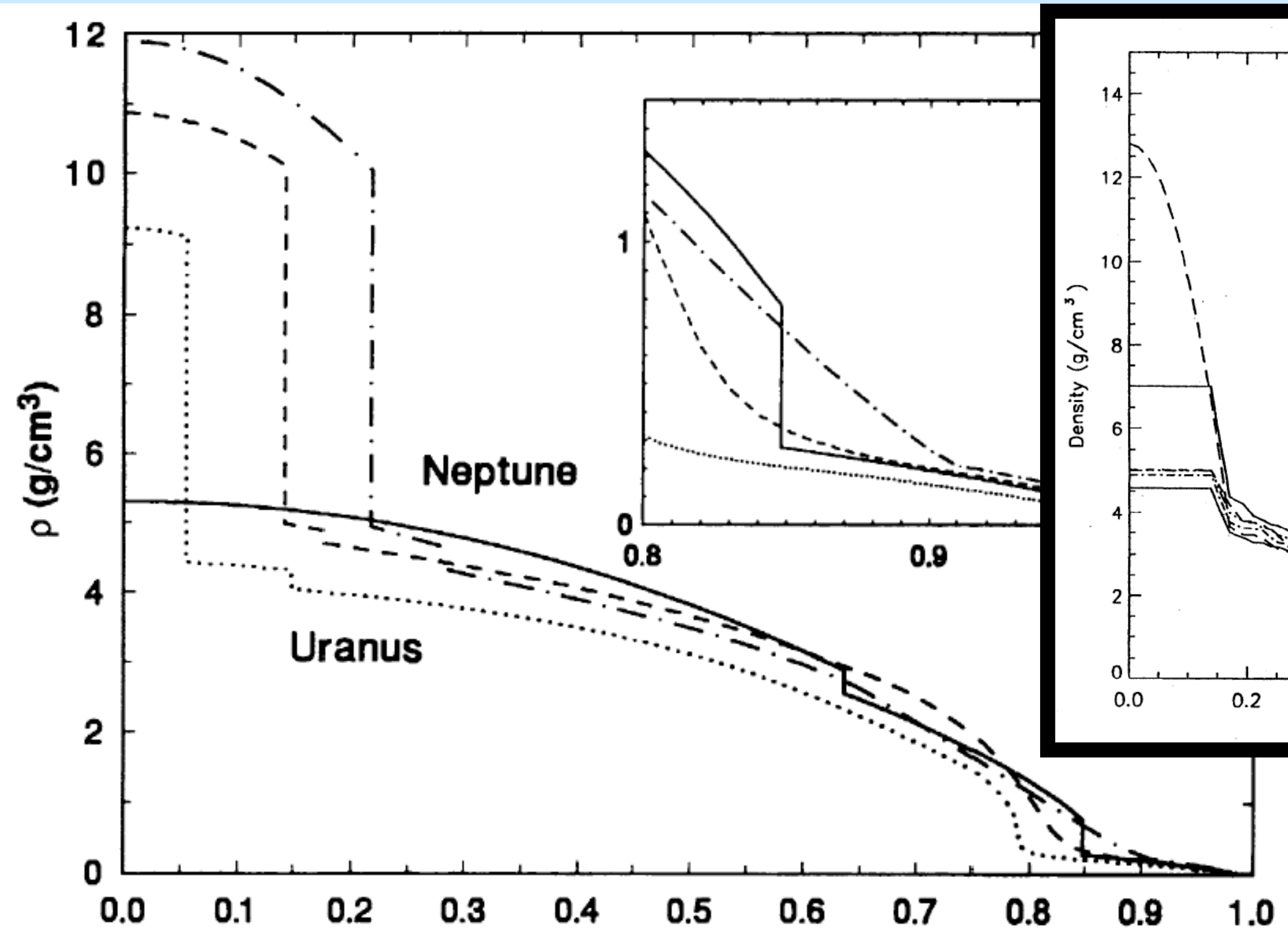
Is the ice in Neptune-class planets solid?

- No.
- All evidence for Uranus/Neptune indicates that their interiors are predominantly fluid
  - A fluid "sea" of partially dissociated fluid H_2O, NH_3, and CH_4
  - This is backed up by models of dynamo-generated magnetic field
  - Experiments by Nellis et al. on water and "synthetic Uranus" mixtures

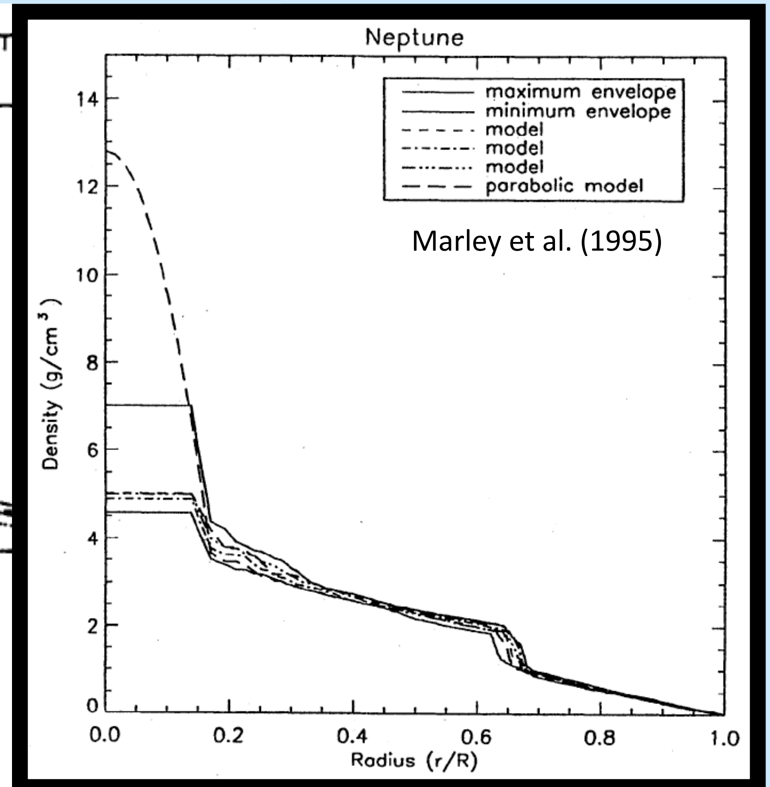


Cavazzoni et al. (1999)

Uncertainties in Understanding the Interiors of Uranus and Neptune

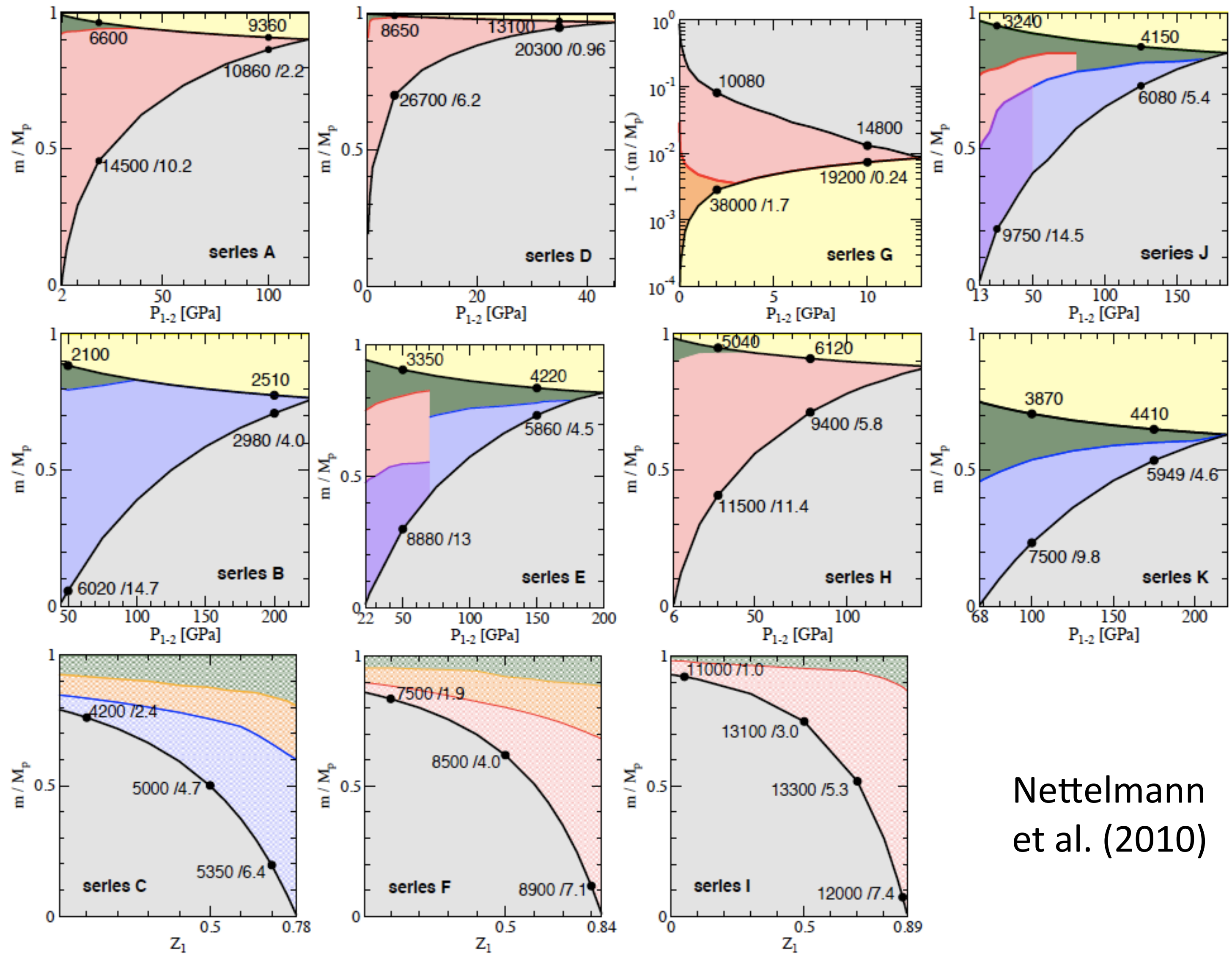


Hubbard et al. (1991)



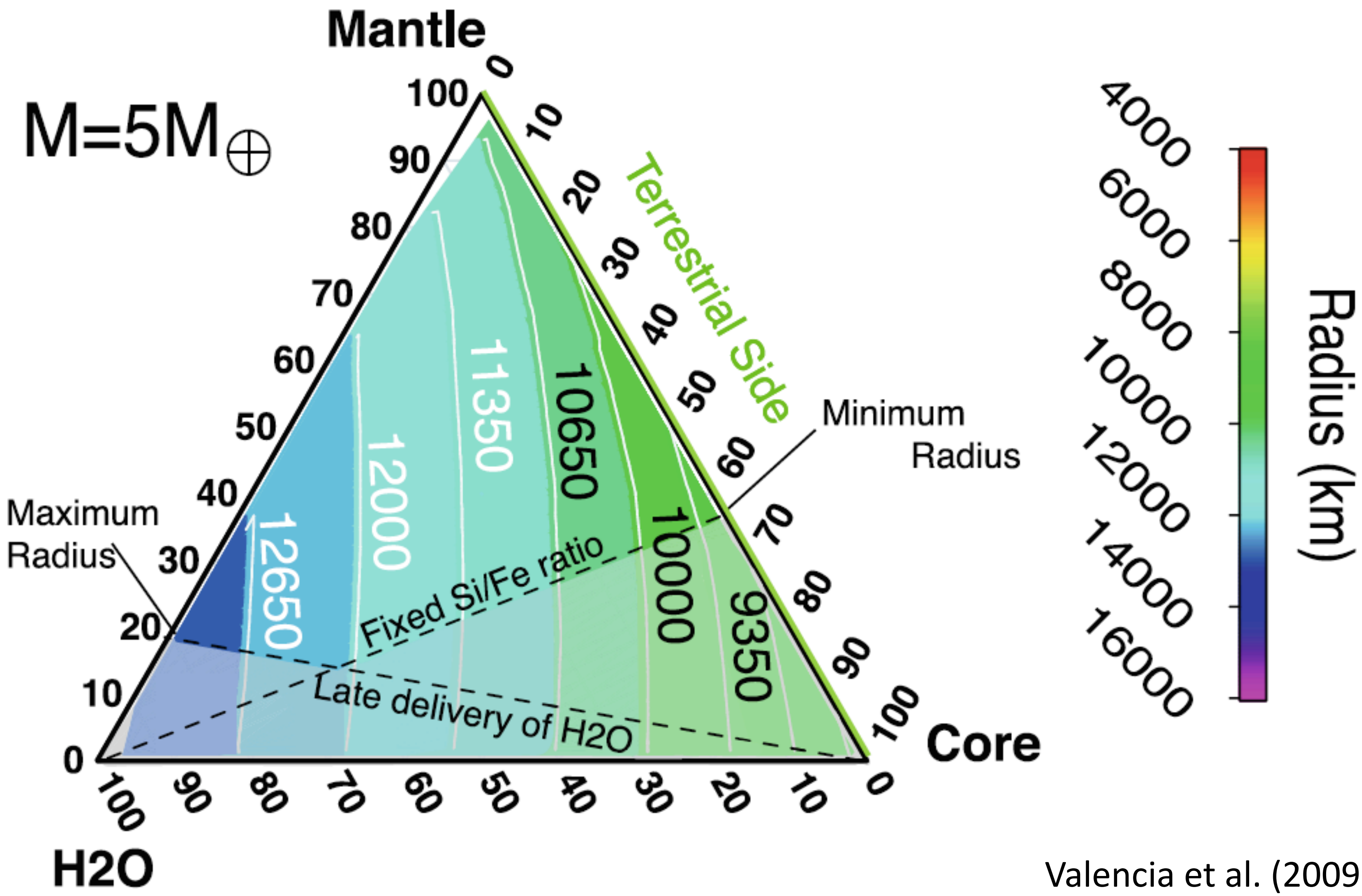
Uranus and Neptune DO NOT have 3 well-defined layers!

Degeneracy: Many compositions yield the same mass/radius



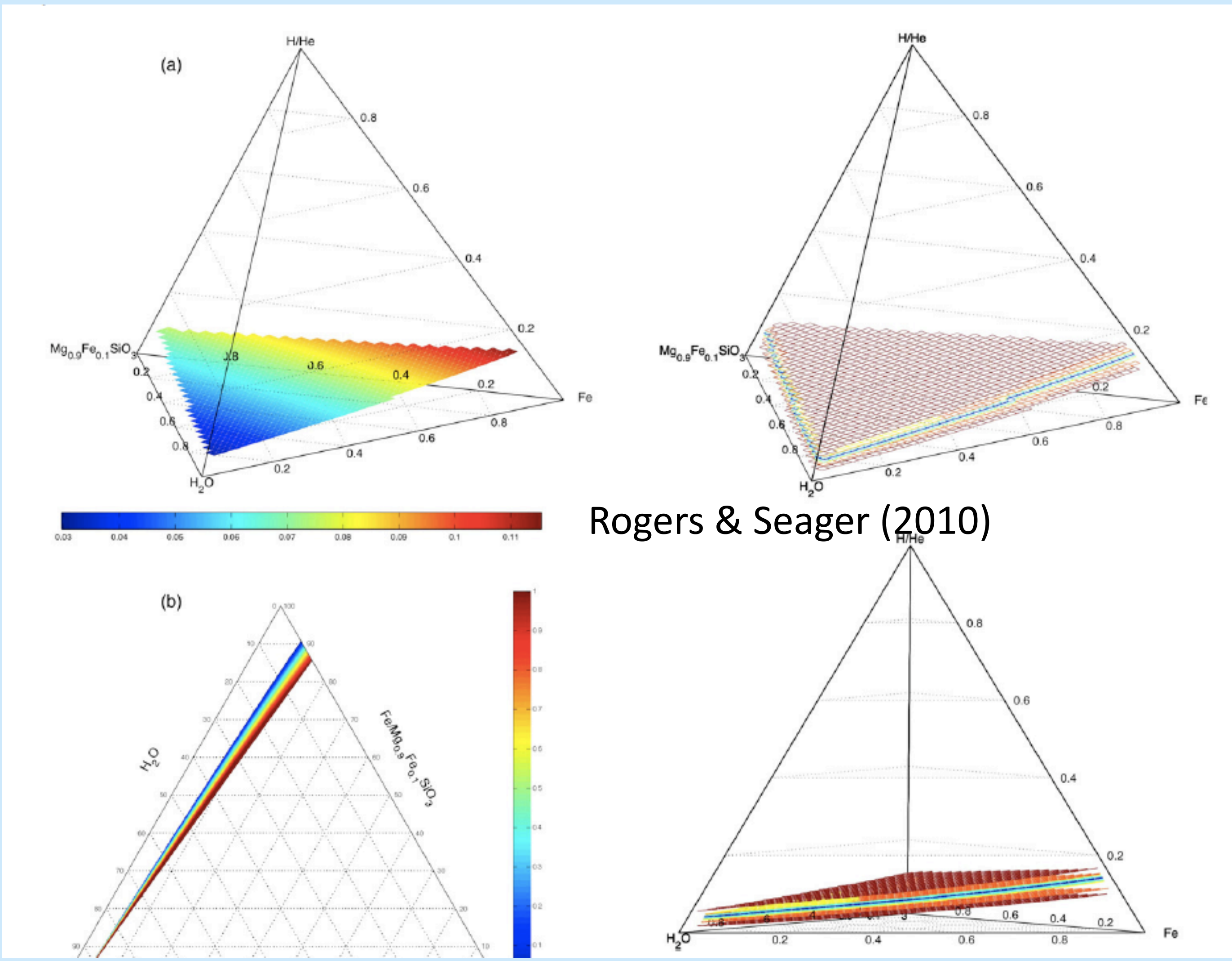
Nettelmann et al. (2010)

Ah, Degeneracy, viewed another way



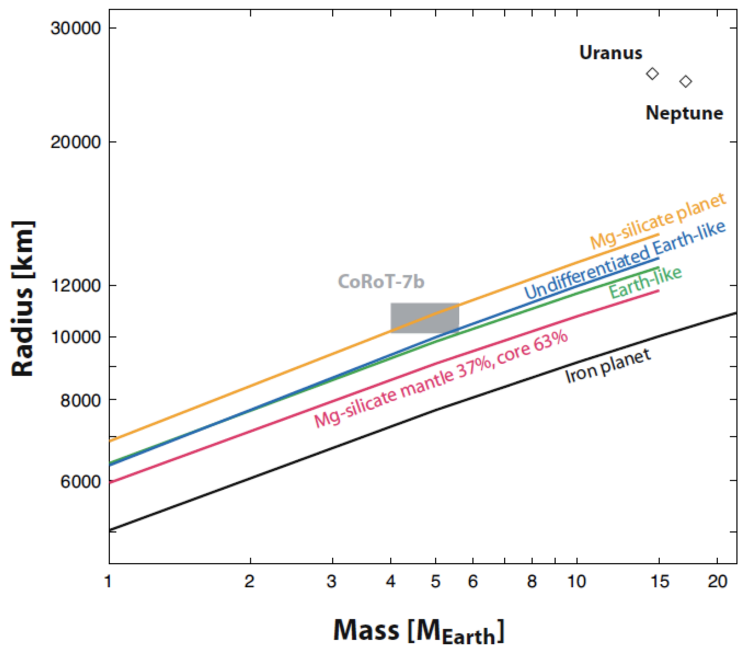
Valencia et al. (2009)

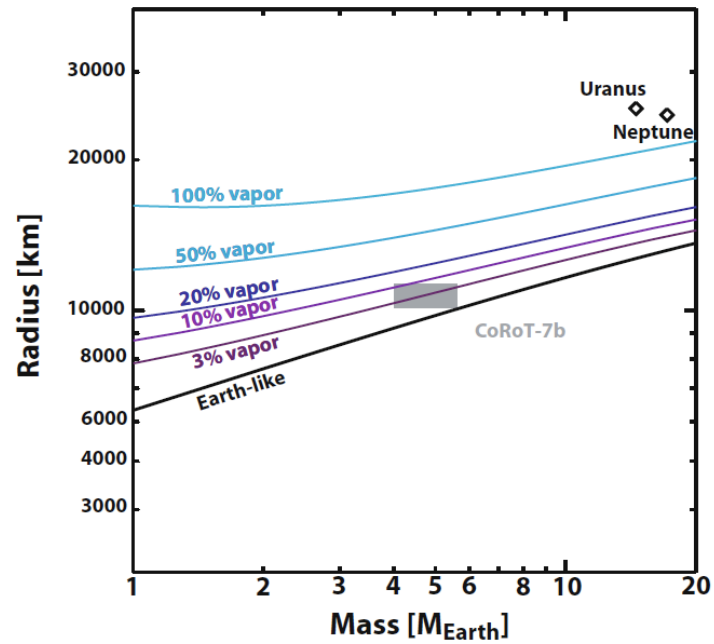
"Exo-Neptunes" Make it Even Worse



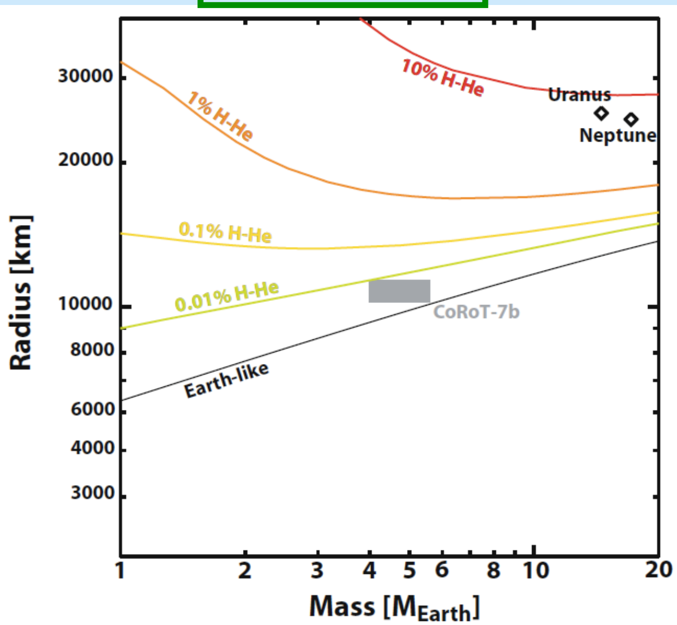
Rogers & Seager (2010)

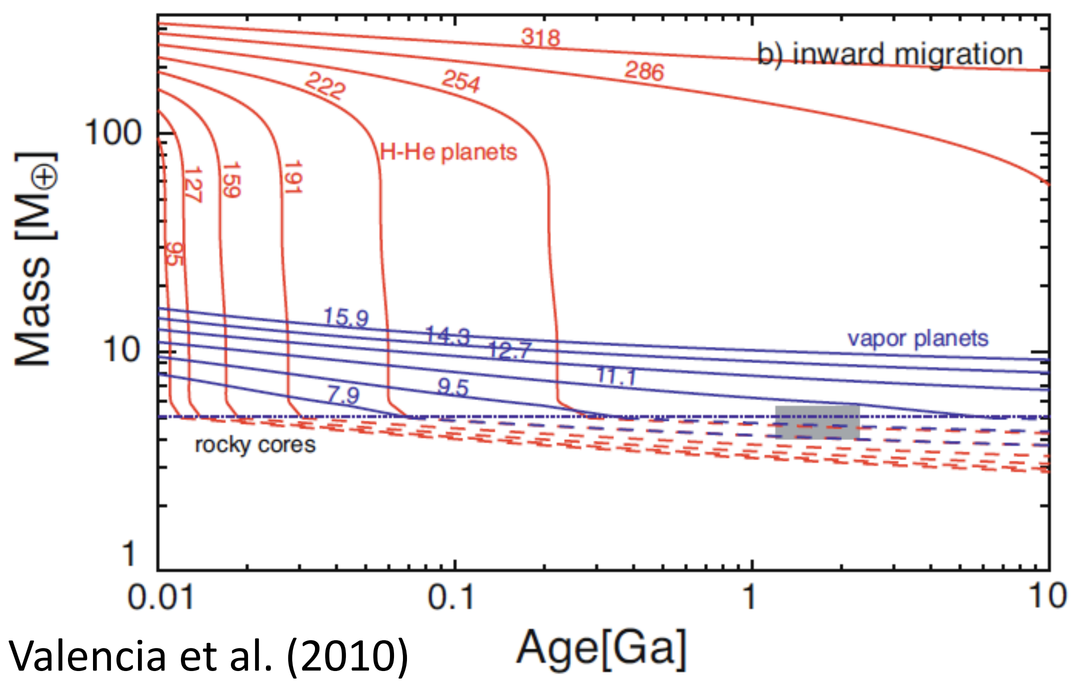
But as we know from Uranus and Neptune, it is actually worse than this





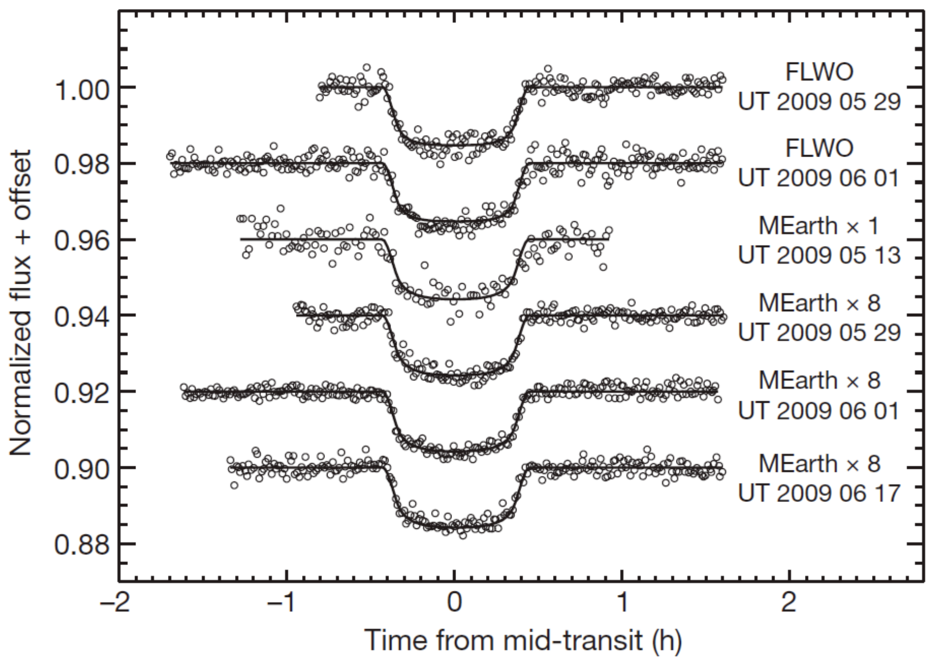
CoRoT-7b



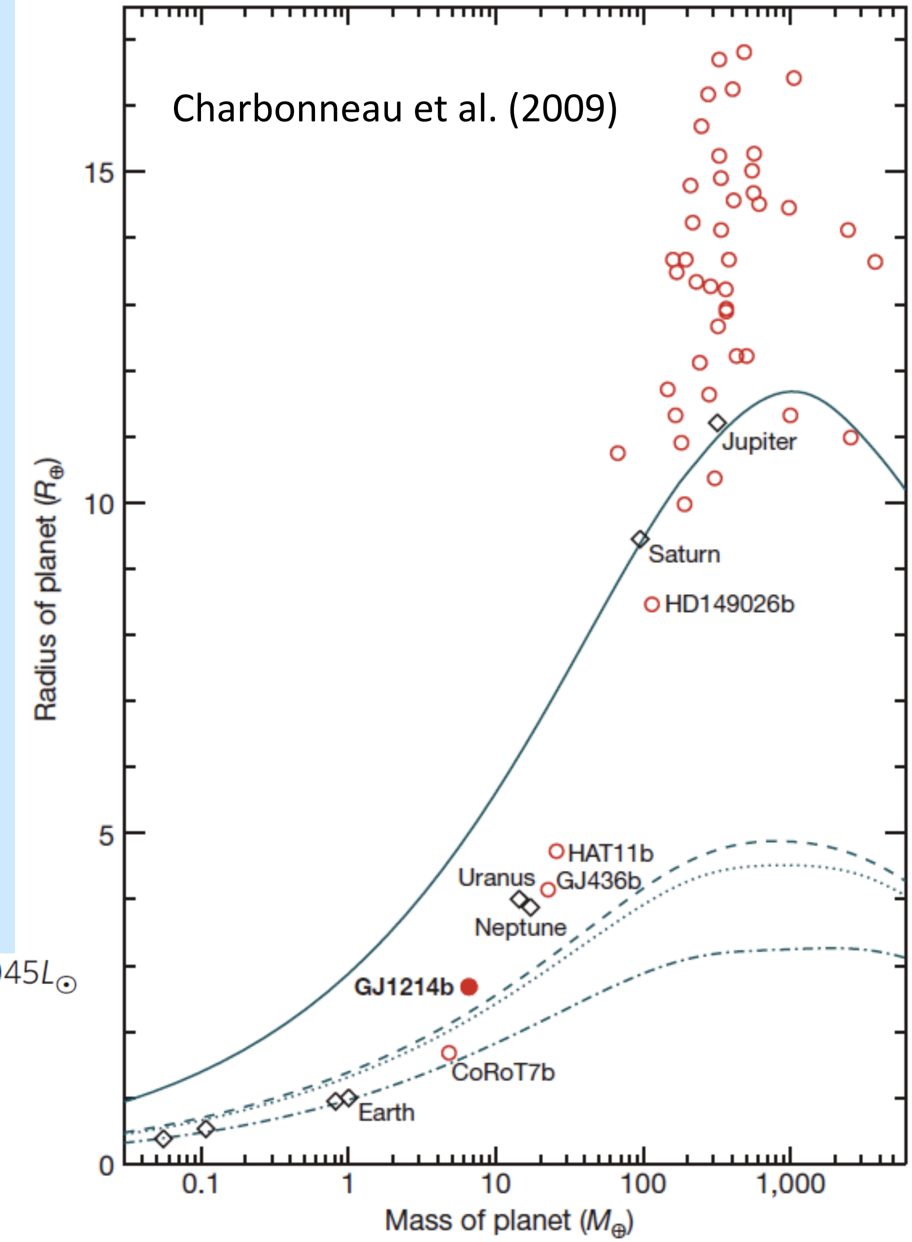


Valencia et al. (2010)

GJ1214b: A "Super Earth" orbiting a nearby bright M star



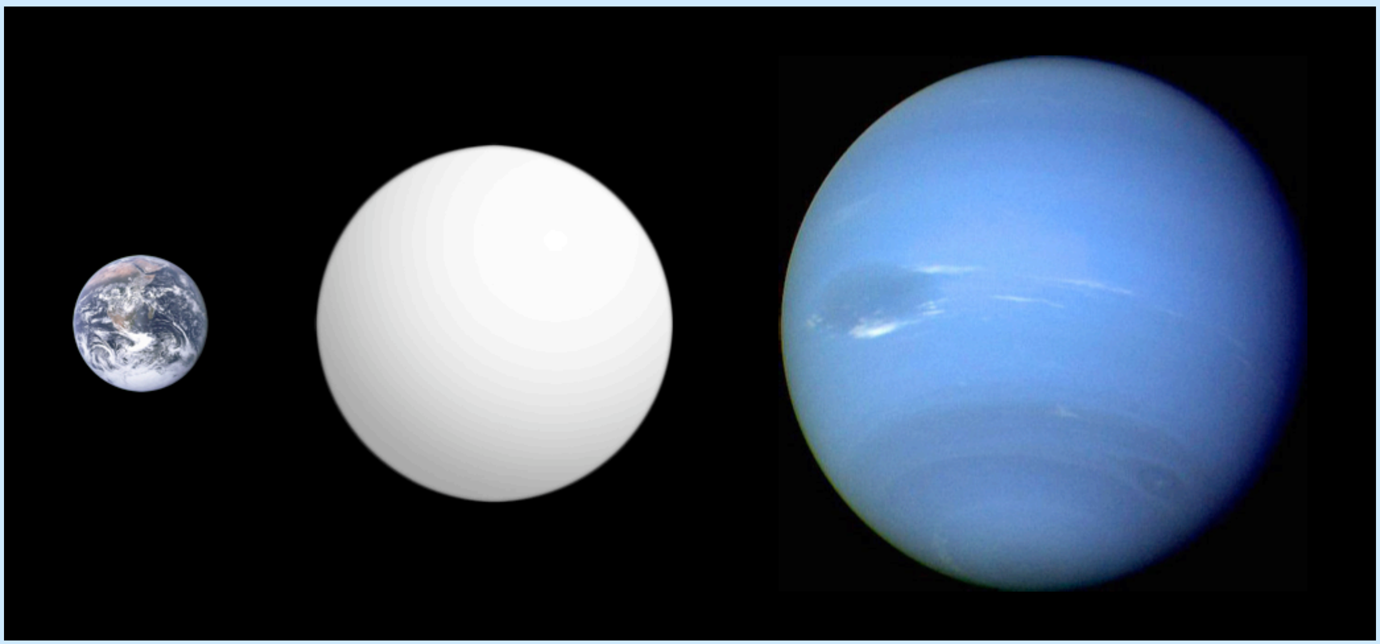
Stellar luminosity, L_s	$0.00328 \pm 0.00045 L_\odot$
Stellar effective temperature, T_{eff} (K)	$3{,}026 \pm 130$
Planetary radius, R_p	$2.678 \pm 0.13 R_\oplus$
Planetary mass, M_p	$6.55 \pm 0.98 M_\oplus$
Planetary density, ρ_p (kg m^{-3})	1870 ± 400
Planetary surface acceleration under gravity, g_p (m s^{-2})	8.93 ± 1.3
Planetary equilibrium temperature, T_{eq} (K)	
Assuming a Bond albedo of 0	555



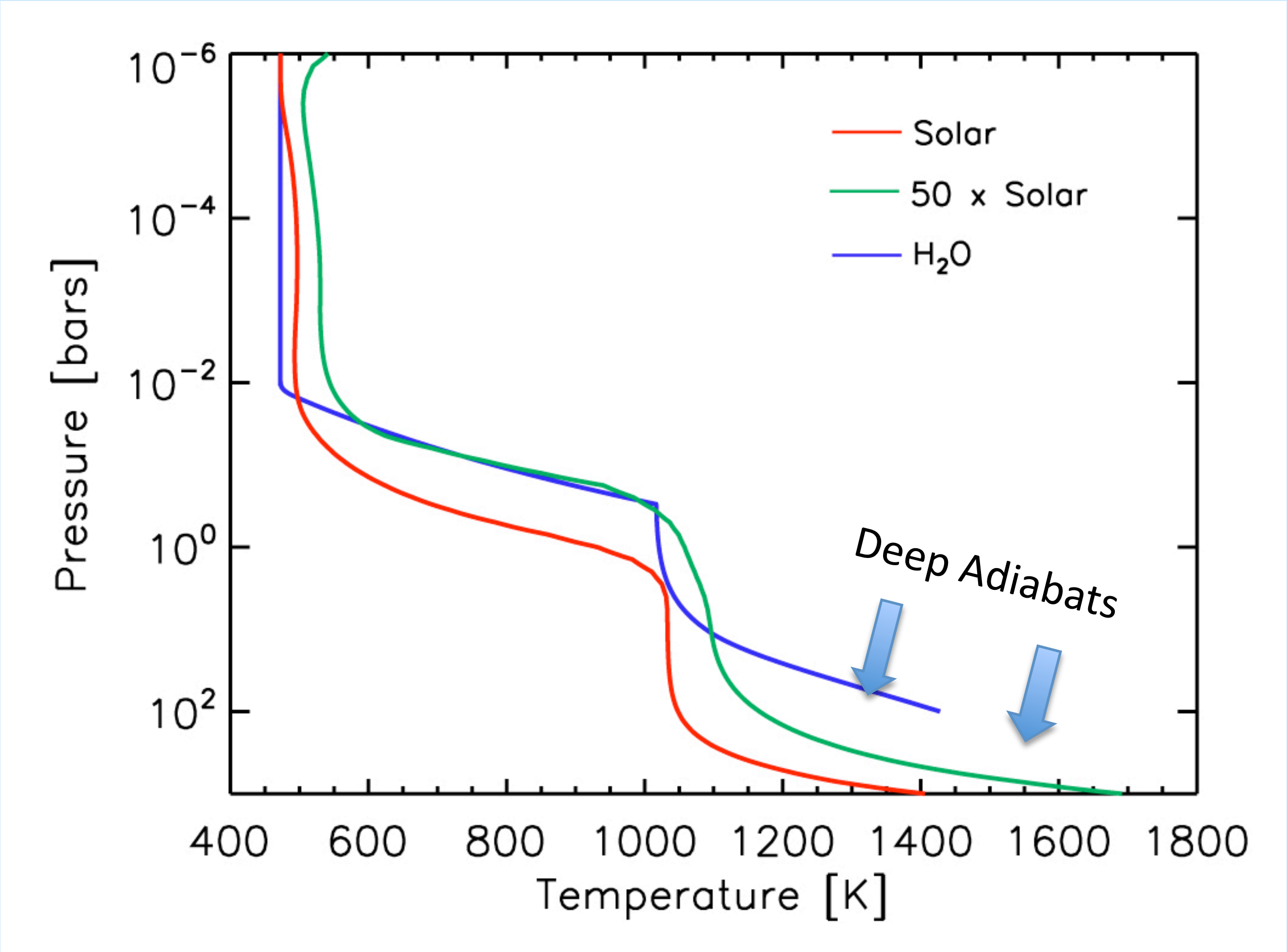
What is the Nature of the Planet's Atmosphere and Interior?

- Mass-Radius leads to degenerate solutions:
    - Mostly water with a small rocky core
        - A "failed" giant planet core?
    - Lower ice/rock ratio, with a H/He envelope
        - A mini Neptune?

What is the cooling history and interior state of these two kinds of models?

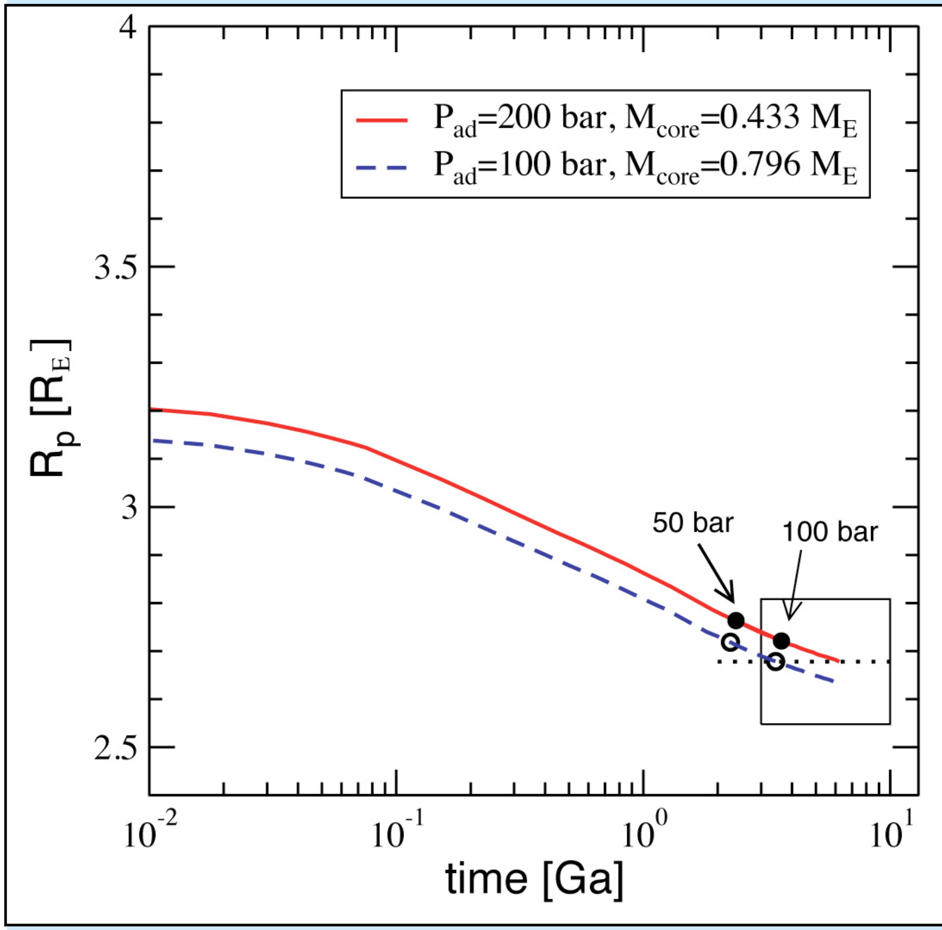


Relation of Atmosphere and Interior

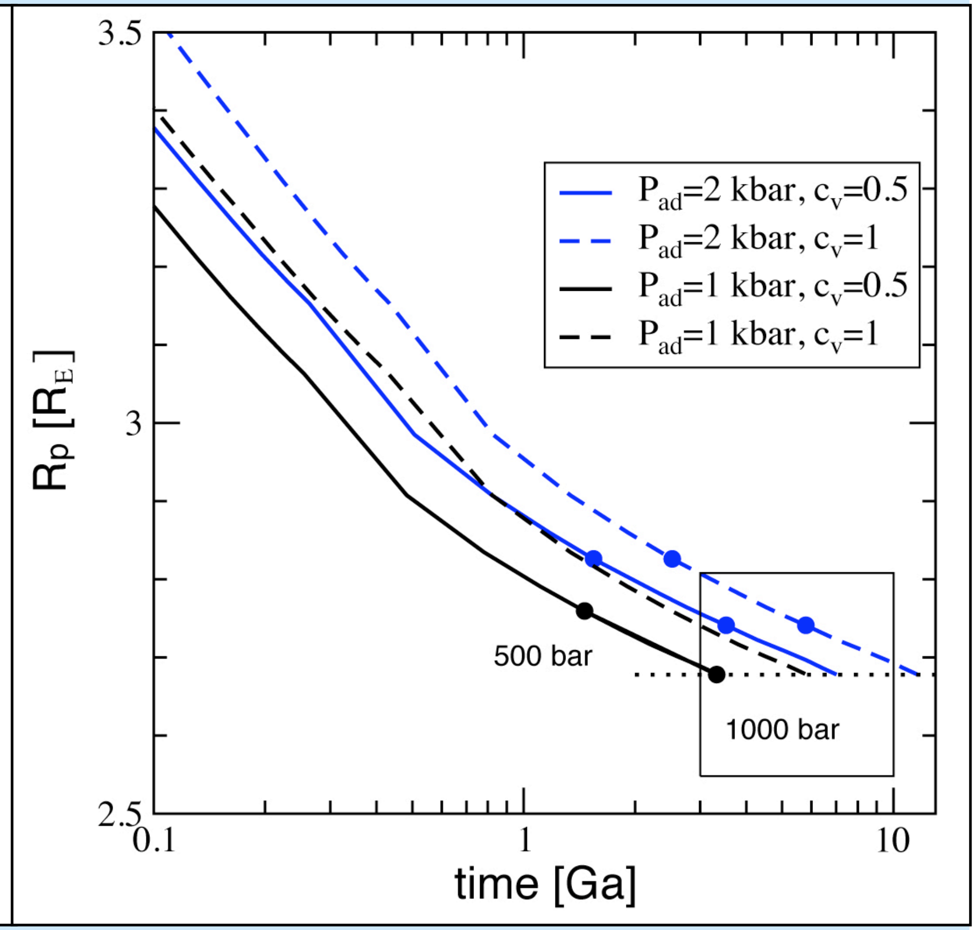


A cooling calculation can show how warm the deep interior is, which helps constrain gas/ice/rock ratios

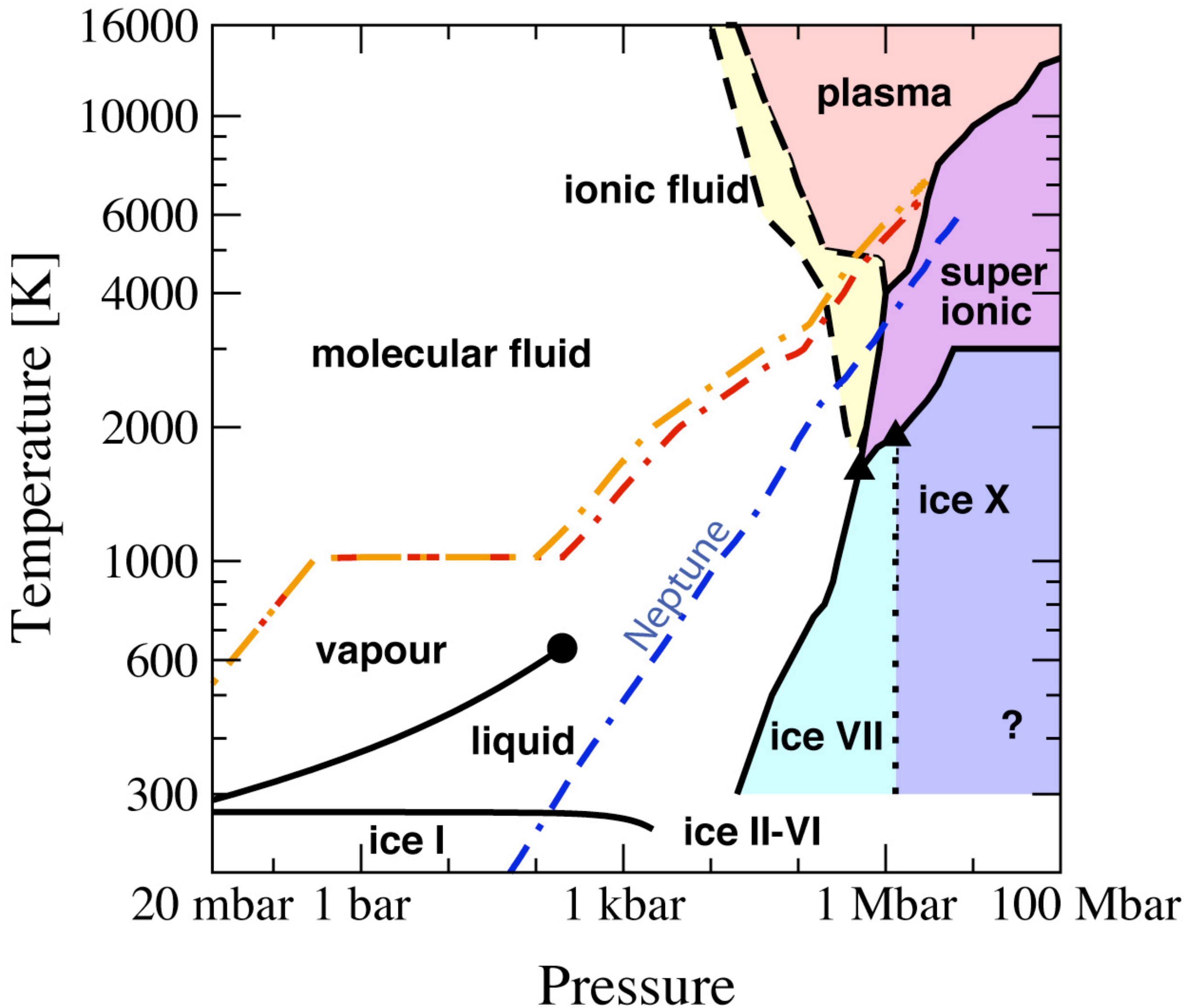
Water World Model



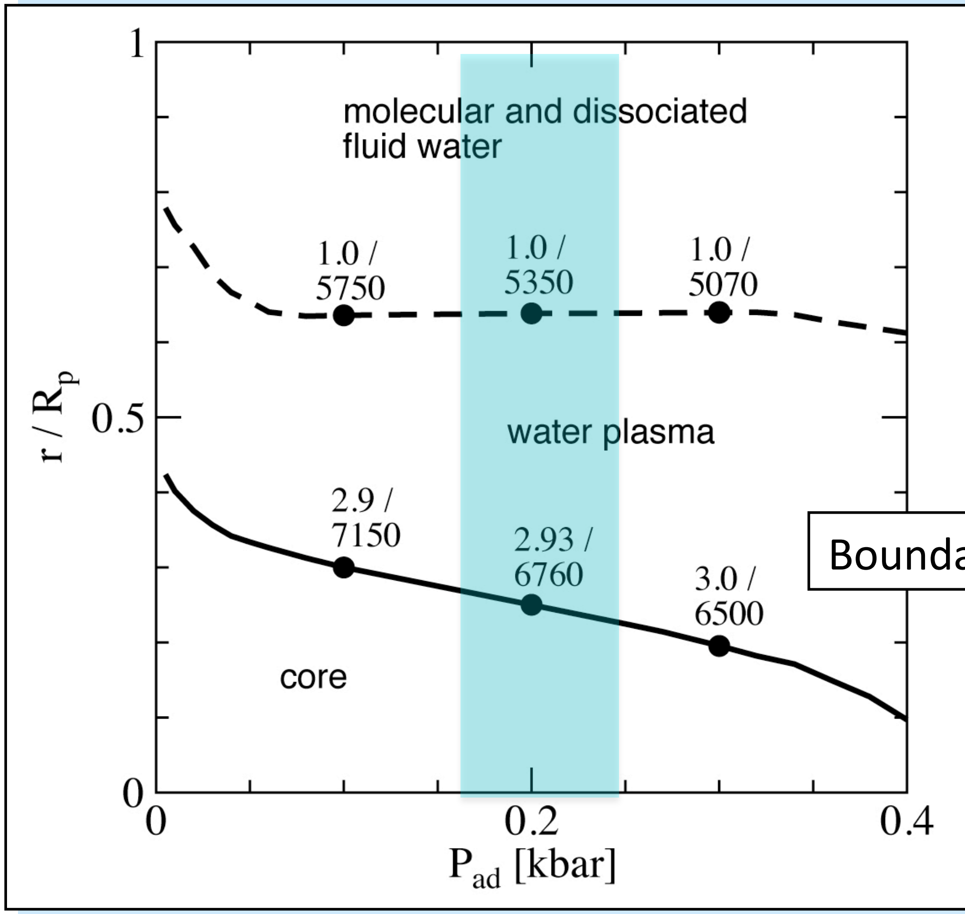
Mini Rocky Neptune Model



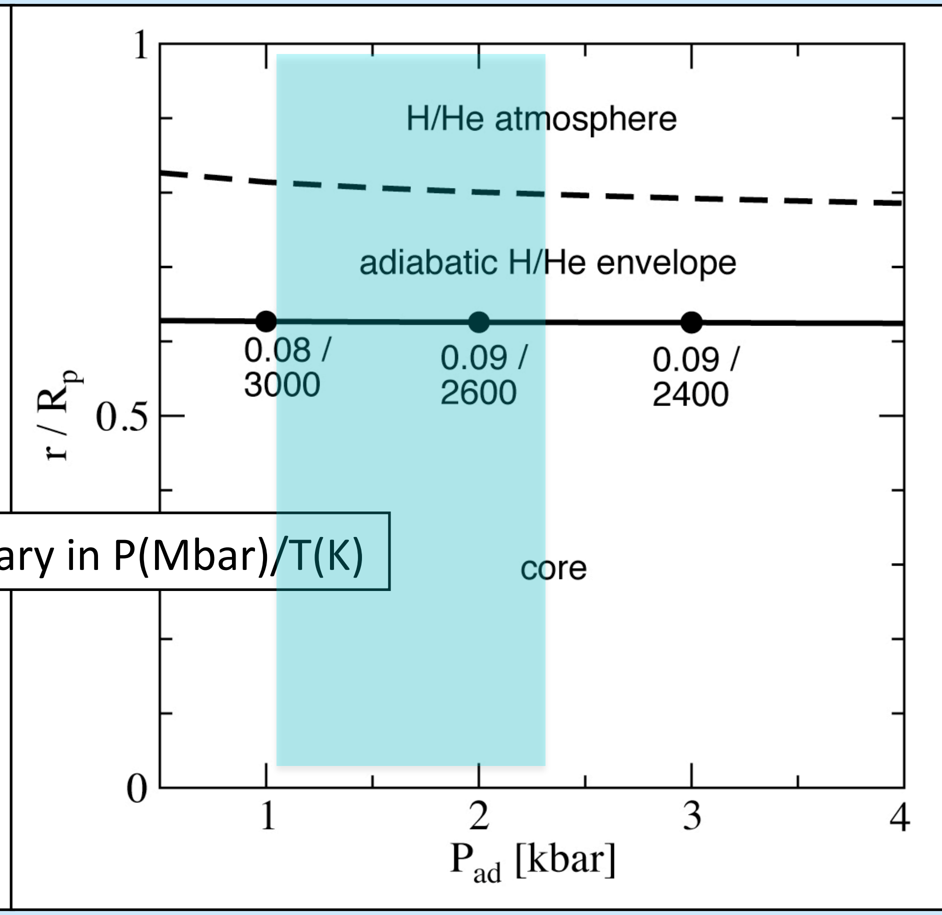
Water World Model



Water World Model

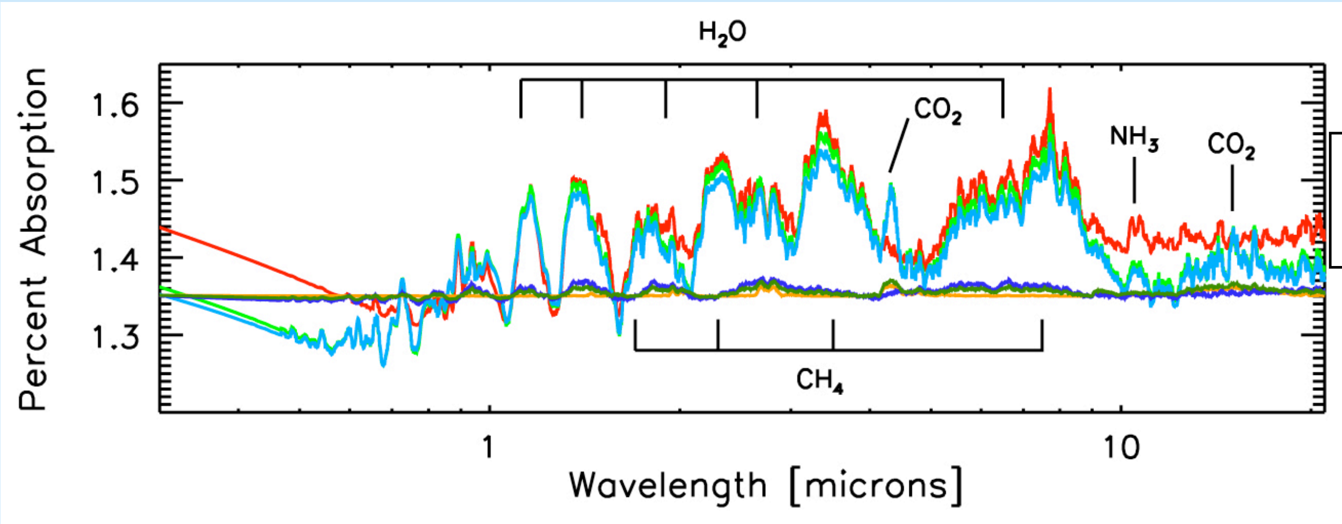


Mini Rocky Neptune Model



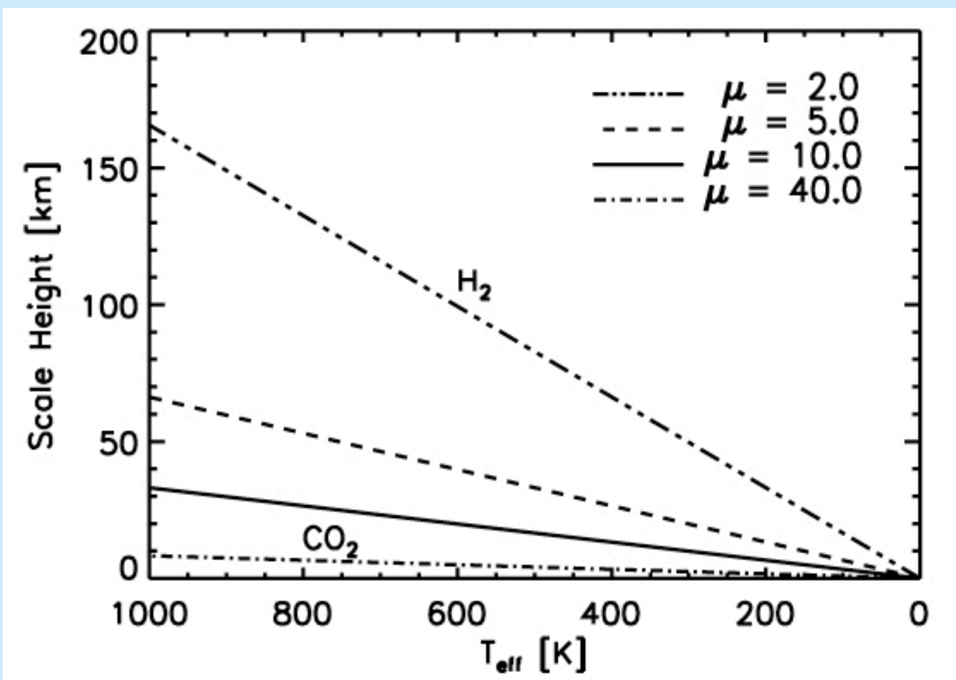
Boundary in P(Mbar)/T(K)

GJ1214b Atmospheric Transmission



H_2/He-dominated atmospheres

Miller-Ricci & Fortney (2010)



Conclusions

- A measurement of mass-radius yields important information about the structure of a gas giants
- Mass-radius tells us little about about the structure of Neptune-class planets, broadly defined
- Tidal heating may be important for a minority of systems
- The hottest planets have the largest radii

- GJ1214b probably does not have a solar system analog
    - (How common are water-rich super Earths?)
    - Very large ice/rock ratio, or
    - Skin of H/He a top rock/ice core
    - Atmosphere will tell us about bulk composition